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ENGINEERING DATA ON NEW AEROSPACE STRUCTURAL MATERIALS

O. L. DEEL and H. MINDLIN

Battelle
Columbus Laboratories

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Air Force Materials Laboratory
Air Force Systems Command
Wright-Patterson Air Force Base, Ohio

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O. L. Deel and H. Mindlin

FOREWORD

This report was prepared by Battelle's Columbus Laboratories, Columbus, Ohio, under Contract F33615-70-C-1070. This contract was performed under Project No. 7381, "Materials Applications", Task No. 738106, "Engineering and Design Data". The work was administered under the direction of the Air Force Materials Laboratory, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio, by Mr. Clayton Harmsworth (AFML/LAE), technical manager.

This final report covers work conducted from January, 1970, to July, 1971. This report was submitted by the authors on November 30, 1971.

This technical report has been reviewed and is approved.

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13. ABSTRACT

The major objectives of this research program were to evaluate newly developed structural materials of potential interest to the Air Force weapons system, and then to provide "data sheet" type presentations of engineering data for these materials. The effort covered in this report has concentrated on Udimet 700 sheet, X5090 sheet, AF2-1DA sheet, Inconel 625 sheet, HA-188 sheet, Custom 455 round bar, PH 14-8 Mo sheet, and Ti-6Al-2Sn-4Zr-2Mo sheet.

The properties investigated include tension, compression, shear, bend, impact, fracture toughness, fatigue, creep and stress-rupture, and stress corrosion at appropriate temperatues.

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14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
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Chemical Composition						
Corrosion Resistance						
Physical Properties						
Aluminum Alloy						
Titanium Alloy						
Nickel Alloy						
Stainless Steel						
Udimet 700						
X5090						
AF2-1DA						
Inconel 625						
HA-188						
Custom 455						
PH 14-8 Mo						
Ti-6Al-2Sn-4Zr-2Mo						

TABLE OF CONTENTS

TABLE OF CONTENTS
(Continued)

LIST OF TABLES

LIST OF TABLES
(Continued)

LIST OF TABLES
(Continued)

LIST OF FIGURES

LIST OF FIGURES

LIST OF FIGURES

LIST OF FIGURES

LIST OF FIGURES

INTRODUCTION

The selection of structural materials to most effectively satisfy new environmental requirements and increased design load requirements for advanced Air Force weapons systems is of vital importance. A major difficulty that design engineers frequently encounter, especially for newly developed materials, materials processing, and product forms, is a lack of sufficient engineering data information to evaluate the relative potential of these developments for a particular application.

The Air Force, in recognition of this need, has sponsored several programs at Battelle's Columbus Laboratories to provide comparative engineering data for newly developed structural materials. The materials included in these programs were carefully selected to insure that they were either available or could become quickly available upon request and that they would represent potentially attractive alloy projections for weapons system usage. The results of these programs have been published in three technical reports, AFML-TR-67-418(1)*, AFML-TR-68-211(2), and AFML-TR-70-252(3).

This technical report is a result of the continuing effort to relieve the above situation and stimulate interest in the use of newly developed alloys, or new processing techniques for older alloys, for advanced structures.

The materials evaluated under this program are as follows:

(1) Udimet 700 sheet

(2) X5090 sheet

(3) AF2-IDA sheet

(4) Inconel 625 sheet

(5) HA-188 sheet

(6) Custom 455 round bar

(7) PH 14-8 Mo sheet

(8) Ti-6Al-2Sn-4Zr-2Mo sheet

The heat-treat or temper conditions selected for evaluation are described in each material section.

The program approach was, as on previous contracts, to search the published literature and to contact metal producers and aerospace companies for any pertinent data. Tests were then scheduled to fill in the gaps in the existing information. Upon completion of each material evaluation, a "data sheet" was issued to make the data immediately available to potential users rather than defer publication to the end of the contract term and the summary technical report. These data sheets are reproduced in the conclusions section of this report.

*Numbers in parentheses refer to references at the end of the text.

Detailed information concerning the properties of interest and test techniques are described in subsequent sections of this report.

EXPERIMENTAL PROCEDURE

Mechanical Properties

The various mechanical properties of interest for each of the materials are as follows:

(1) Tension

(a) Tensile ultimate strength, TUS

(b) Tensile yield strength, TYS

(c) Elongation, e_t

(d) Reduction in area, RA

(e) Modulus of elasticity, E_t.

(2) Compression

(a) Compressive yield strength, CYS

(b) Modulus of elasticity, E_c.

(3) Creep and stress-rupture

(a) Stress for 0.2 or 0.5 percent deformation in 100 hours and 1000 hours

(b) Stress for rupture in 100 hours and 1000 hours.

(4) Shear

(a) Shear ultimate strength, SUS

(5) Axial fatigue*

(a) Unnotched, R = 0.1, lifetime: 10^3 through 10^7 cycles

(b) Notched (K_t = 3.0), R = 0.1, lifetime: 10^3 through 10^7 cycles

---

*"R" represents the algebraic ratio of the minimum stress to the maximum stress in one cycle; that is, $R = S_{min}/S_{max}$. "K_t" represents the Neuber-Peterson theoretical stress concentration factor.

(6) Fracture toughness, K_{Ic} or K_c

(7) Stress corrosion

(a) 80 percent TYS for 1000 hours maximum, 3-1/2 percent NaCl solution.

(8) Thermal expansion.

(9) Bend

(a) Minimum radius.

(10) Impact

(a) Charpy V-notch.

(11) Density.

Specimen Identification

A simple system of numbers and letters was used for specimen identification. Coding consisted of a number indicating the type of test and also indicating a comparable area on the sheet, plate, or forging. For certain test types, the number was followed by a letter signifying specimen orientation (L for longitudinal, T for transverse, ST for short transverse). The test types where the letter did not appear were creep, fatigue, and bend since, in these cases, only one specimen orientation was used. The next number in the coding specifies the location from which the specimen blank was taken from the original material configuration. Coding was as follows:

Assigned Number	Test Type
1	Tension
2	Compression
3	Creep and stress-rupture
4	Shear
5	Fatigue
6	Fracture toughness
7	Stress corrosion
8	Thermal expansion

Assigned Number	Test Type
9	Bend
10	Impact
11	Density

As an example, a specimen numbered 2-T5 is a compression specimen, transverse orientation, cut from Location 5. Also, a specimen numbered 5-12 is a fatigue specimen cut from Location 12.

Specimen designs used in this program are shown in Figures 1 through 18. These specimens conform to dimensional and tolerance specifications outlined in relevent ASTM Standards, in Federal Test Method Standard No. 151a, in AIA Publication ARTC-13[4], or in MAB Publication MAB 192-M[5].

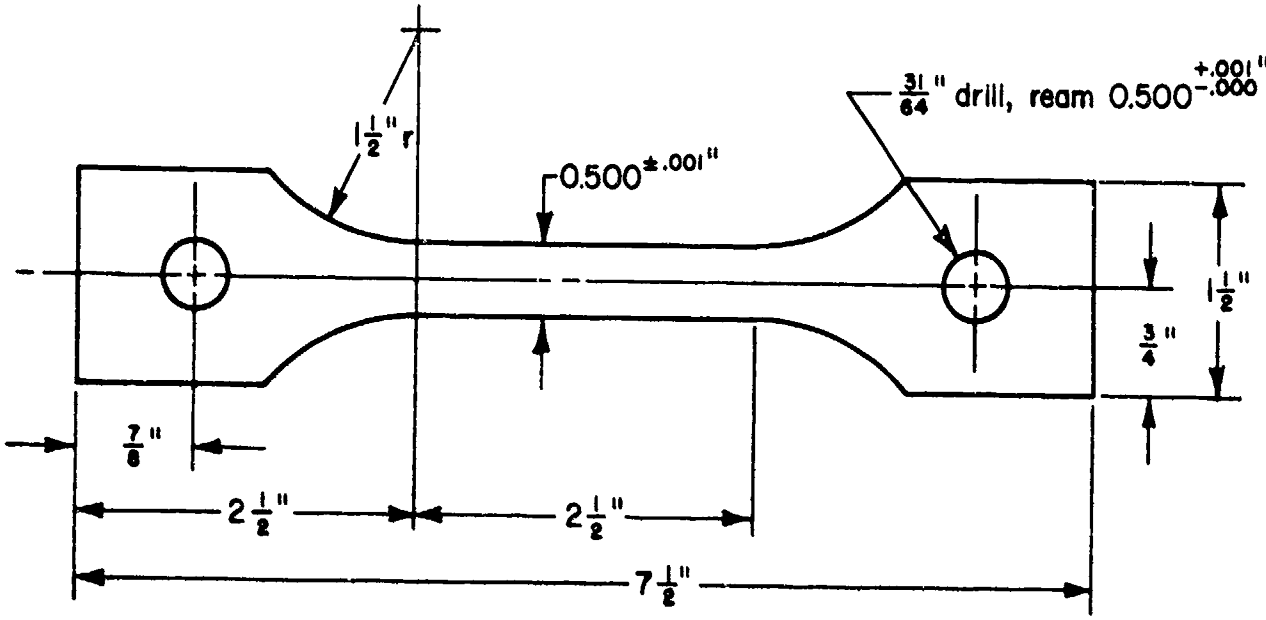
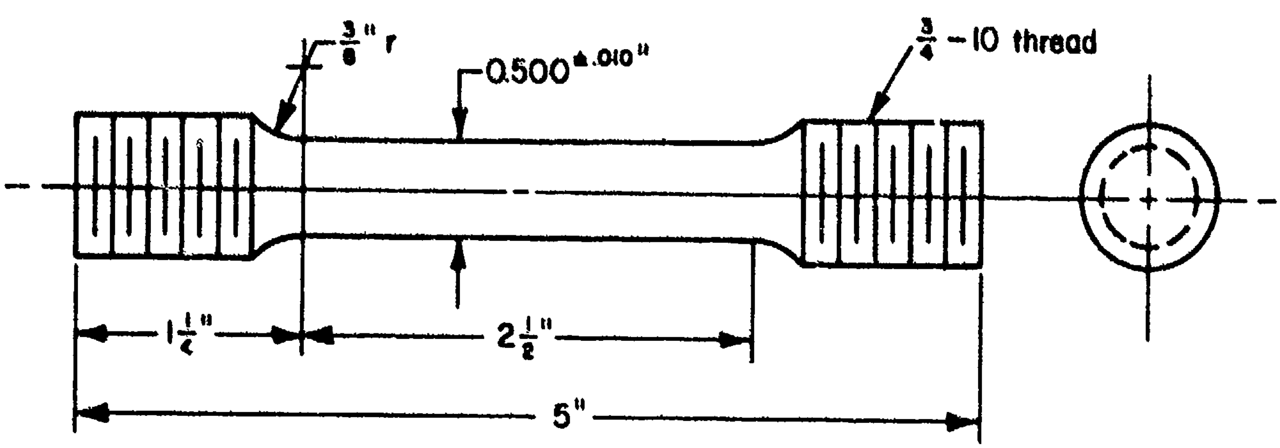
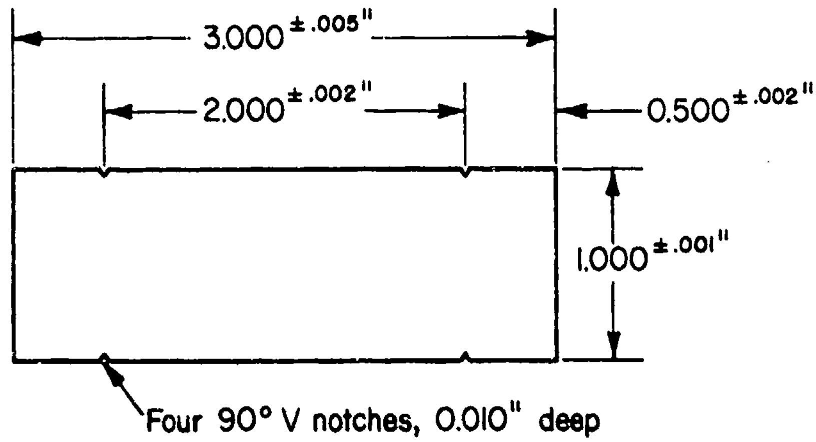


FIGURE 1. SHEET AND THIN-PLATE TENSILE SPECIMEN



A-1002

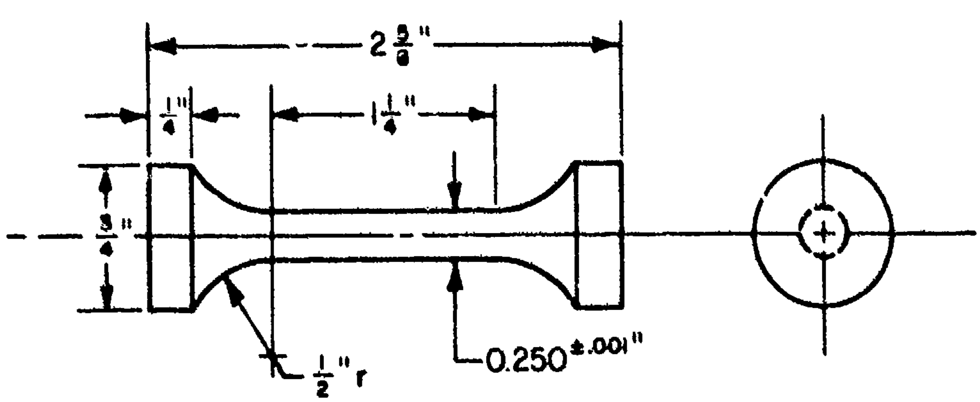
FIGURE 2. ROUND TENSILE SPECIMEN



Notes: 1. Ends must be flat and parallel to within 0.0002".

2. Surface must be free from nicks and scratches.

FIGURE 3. SHEET COMPRESSION SPECIMEN



Note: Ends to be flat and parallel to within 0.0002" of ℄

A-1003

FIGURE 4. ROUND COMPRESSION SPECIMEN

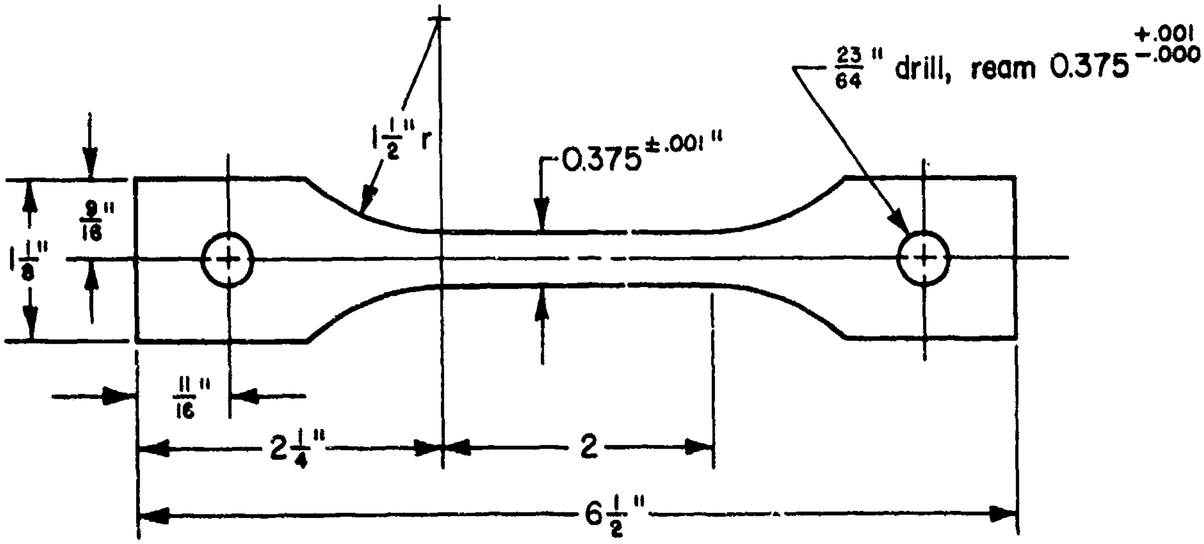


FIGURE 5. SHEET CREEP- AND STRESS-RUPTURE SPECIMEN

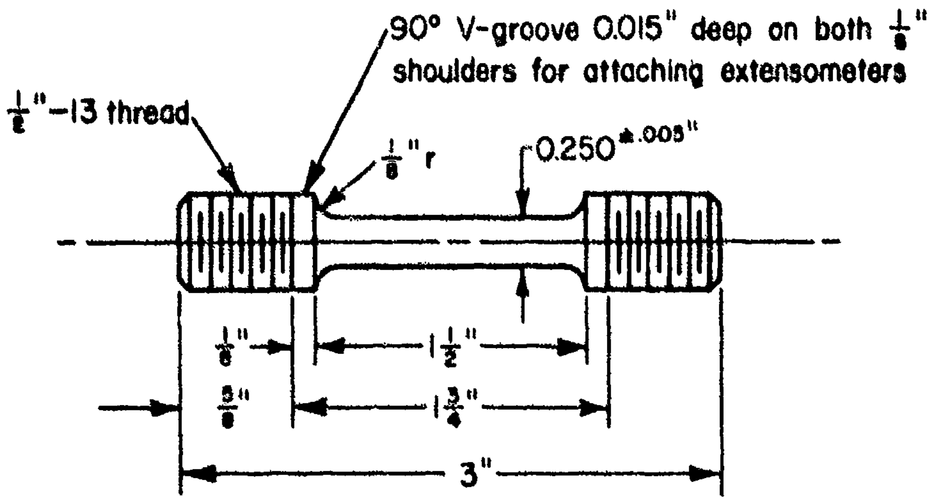


FIGURE 6. ROUND CREEP- AND STRESS-RUPTURE SPECIMEN

A-1004

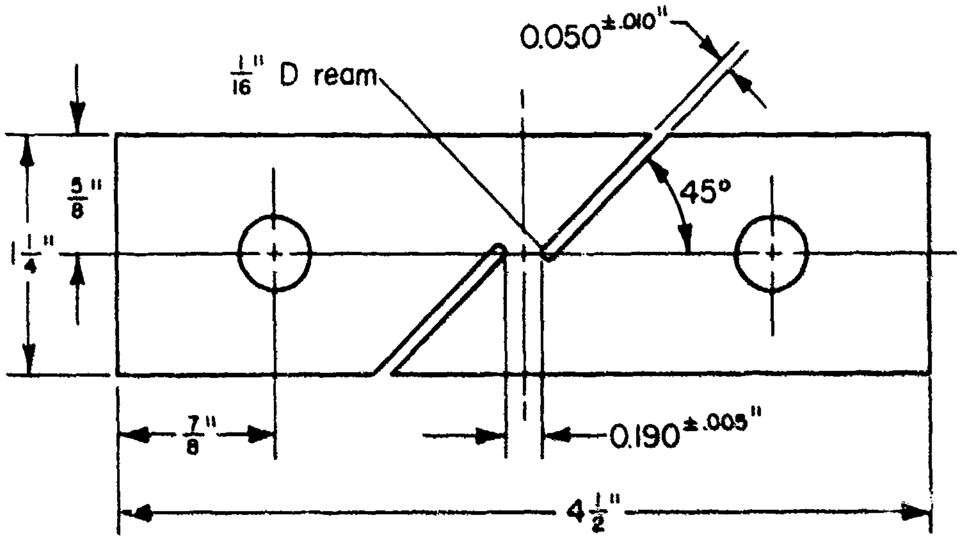


FIGURE 7. SHEET SHEAR TEST SPECIMEN

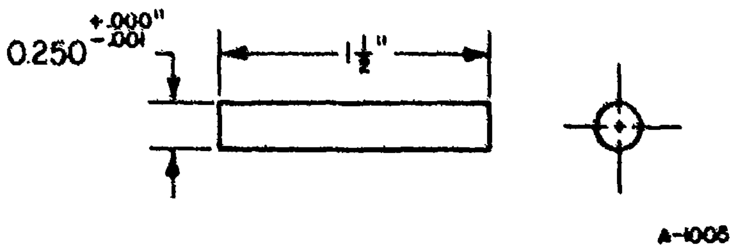


FIGURE 8. PIN SHEAR SPECIMEN

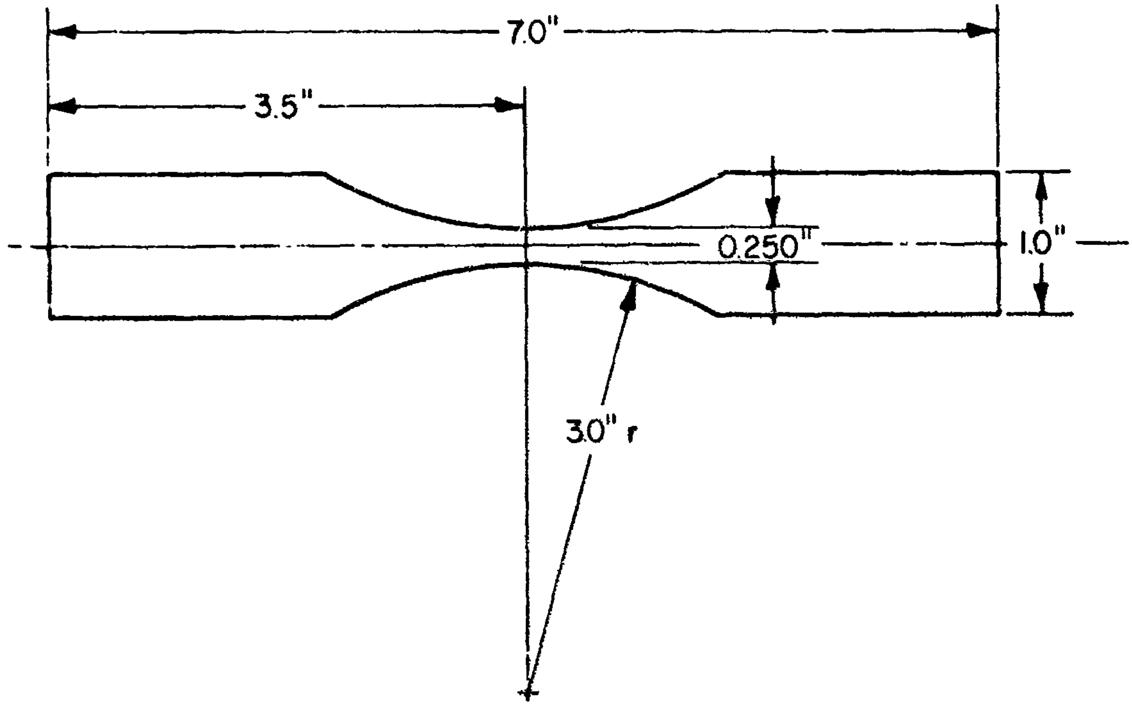


FIGURE 9. UNNOTCHED SHEET FATIGUE SPECIMEN

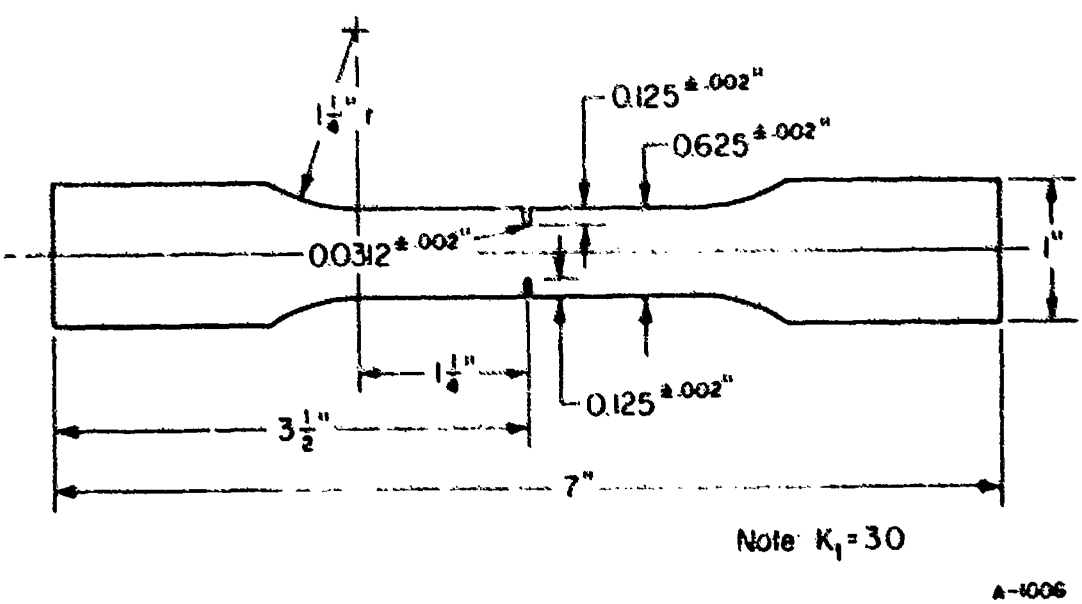


FIGURE 10. NOTCHED SHEET FATIGUE SPECIMEN

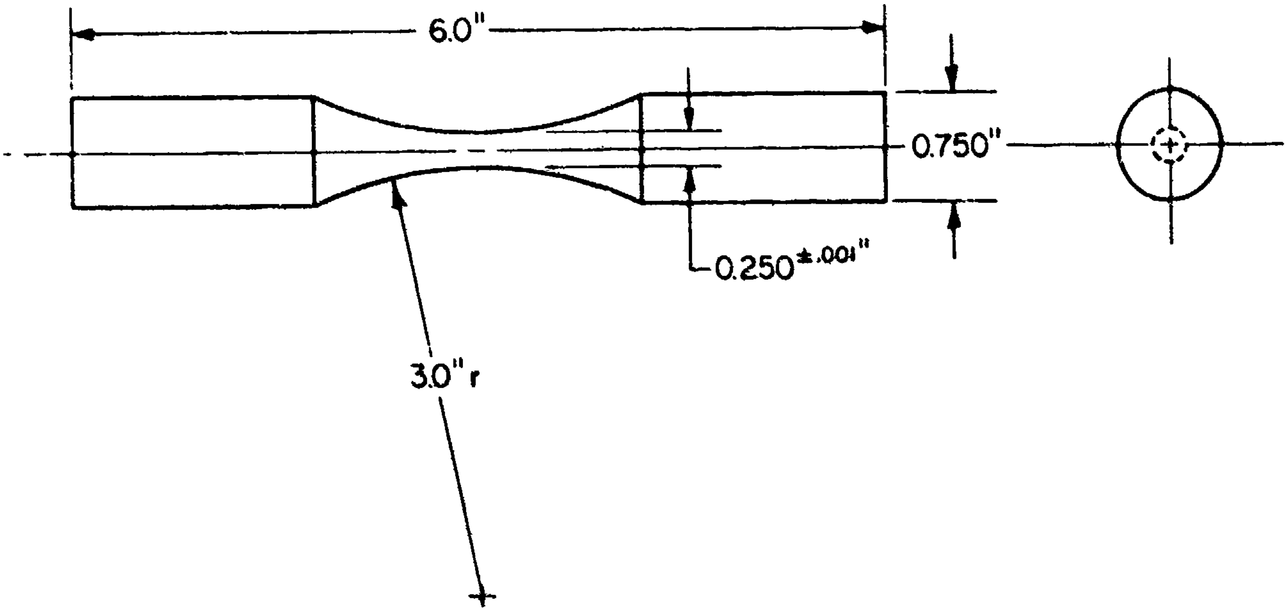


FIGURE 11. UNNOTCHED ROUND FATIGUE SPECIMEN

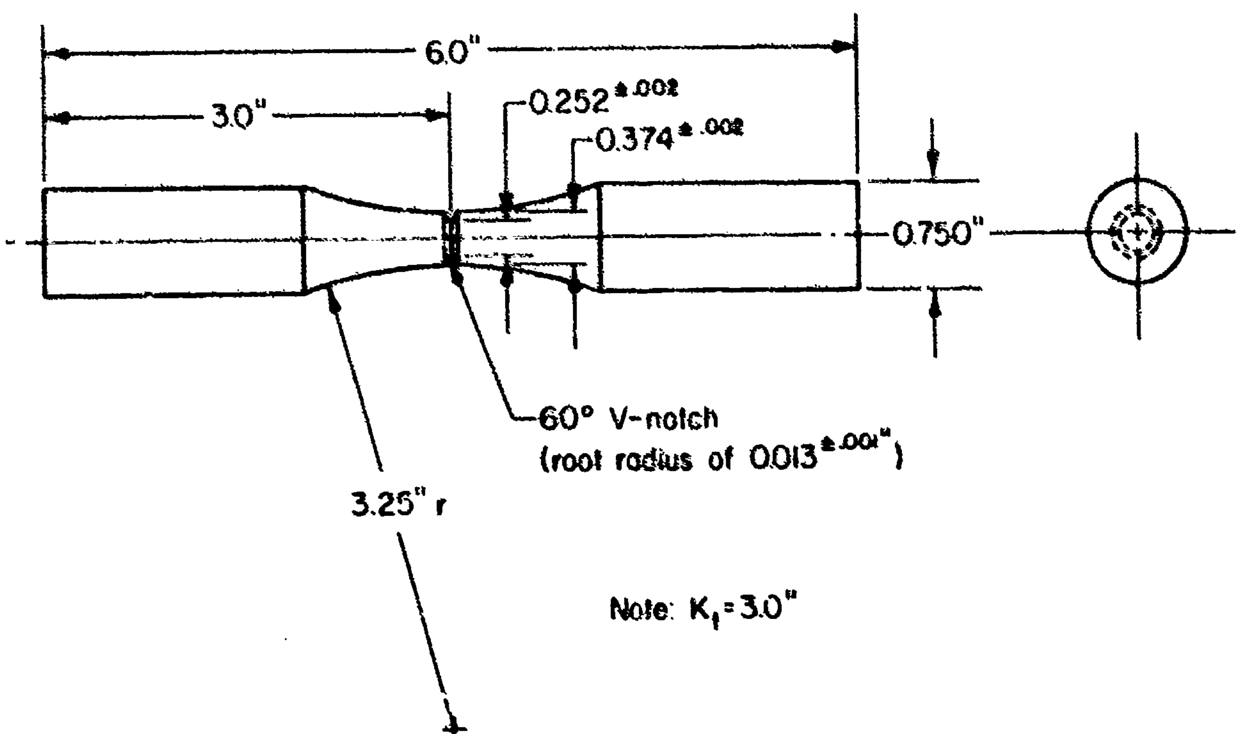


FIGURE 12 NOTCHED ROUND FATIGUE SPECIMEN

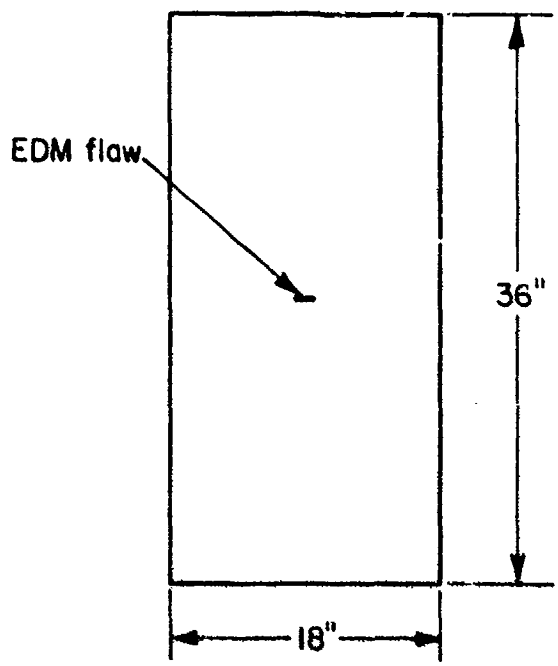


FIGURE 13. SHEET FRACTURE TOUGHNESS SPECIMEN

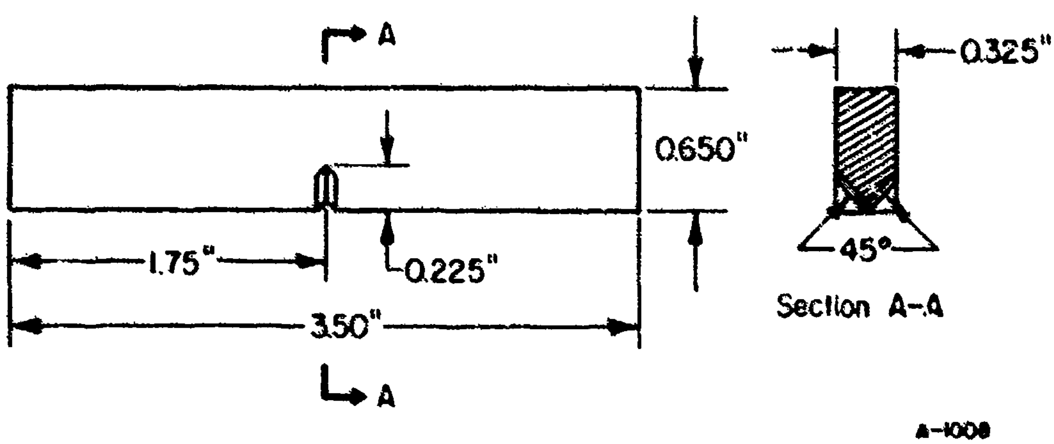


FIGURE 14. SLOW BEND FRACTURE TOUGHNESS SPECIMEN

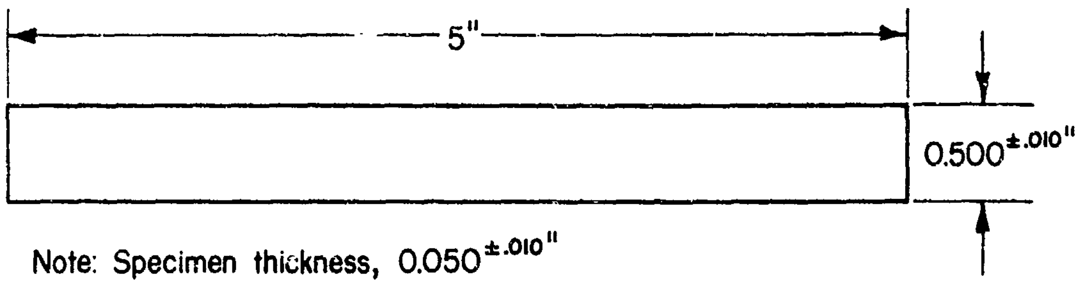


FIGURE 15. STRESS-CORROSION SPECIMEN

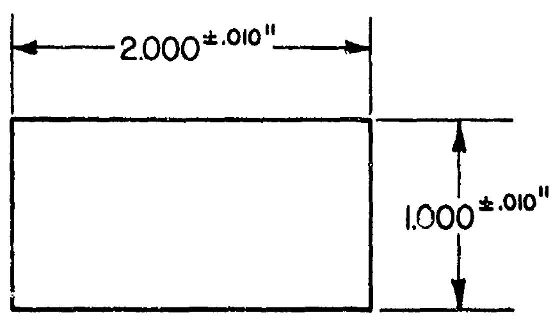


FIGURE 16. THERMAL-EXPANSION SPECIMEN

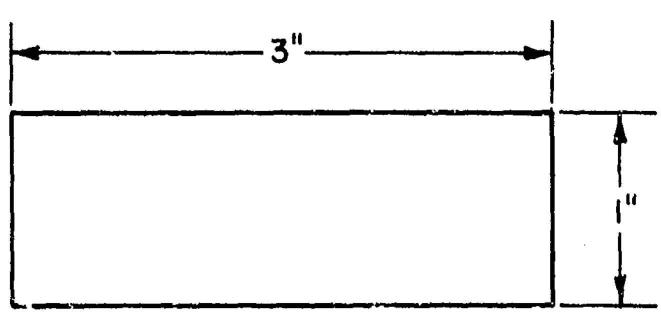


FIGURE 17. SHEET BEND SPECIMEN A-1009

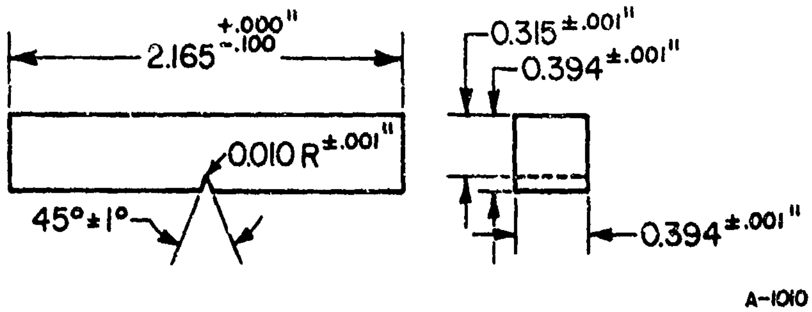


FIGURE 18. NOTCHED IMPACT SPECIMEN

Test Description

Tension

Procedures used for tension testing are those recommended in ASTM methods E8-68 and E21-66T as well as in Federal Test Method standard No. 151a (method 211.1). Six specimens (three longitudinal and three transverse) were tested at each temperature to determine ultimate tensile strength, 0.2 percent offset yield strength, elongation, and reduction in area. The modulus of elasticity was obtained from load-strain curves plotted by an autographic recorder during each test.

All tensile tests were carried out in Baldwin Universal testing machines. These machines are calibrated at frequent intervals in accordance with ASTM method E4-64 to assure loading accuracy within 0.2 percent. The machines are equipped with integral automatic strain pacers and autographic strain recorders.

Specimens tested at elevated temperatures were heated in standard wire-wound resistance-type furnaces. Each furnace was equipped with a Foxboro controller capable of maintaining the test temperature to within 5 F of the control temperature over a 2-inch gage length. Chromel-Alumel thermocouples attached to the specimen gage section were used to monitor temperatures. Each specimen was soaked at temperature at least 20 minutes before being tested.

An averaging-type linear differential transformer extensometer was used to measure strain. For elevated temperature testing, the extensometer was equipped with extensions to bring the transformer unit out of the furnace. The extensometer conformed to ASTM E3-64T Classification B1 having a sensitivity of 0.0001 inch/inch. The strain rate in the elastic region was maintained at 0.005 inch/inch/minute. After yielding occurred, the head speed was increased to 0.1 inch/inch/minute until fracture.

Compression

Procedures for conducting compression tests are outlined in ASTM Method E9-67 along with temperature control provisions of E21-66T. All sheet and thin plate tests were carried out in Baldwin Universal testing machines using a North American type compression fixture as shown in Reference 2. Specimen heating was accomplished by a forced-air furnace for temperatures up to 1000F. Specimen temperature was maintained by means of a Wheelco pyrometer. Three Chromel-Alumel thermocouples attached to the fixture were used to monitor temperatures to within 3F of the test temperature. For higher temperatures, wire-wound furnaces were used with controls as described in the tensile test section.

The extensometer used for the compression tests was quite similar to that used in the tensile testing. The extension arms were fastened to the specimen at small notches spanning a 2-inch gage length. The output from the microformer was fed into a load-strain recorder to provide autographic load-strain curves. During testing the strain rate was adjusted to 0.005 inch/inch/minute.

For bar and forging material, cylindrical specimens similar to those described in ASTM E9-67 were used with appropriate temperature control and strain measurement as described above.

Six specimens (three longitudinal and three transverse) were tested at each temperature.

Shear

Single-shear sheet-type specimens were used for sheet and thin-plate material; for bar and forgings, a double-shear pin-type was used. Shear testing was performed at room temperature only. A minimum of six specimens (three longitudinal and three transverse) were used to determine ultimate shear strength.

Bend

The procedures for conducting bend tests are described in Report MAB-192-M. The specimens were placed in a rigid three-point loading fixture and bending tups of various sizes were used to determine the minimum bend radius at room temperature.

Creep and Stress Rupture

Standard dead-weight type creep testing frames were used for the creep and stress-rupture tests. These machines are calibrated to operate well within the accuracy requirements of ASTM method E139-66T.

Specimens similar to those used for tension tests were used for the creep and stress-rupture studies. A platinum strip "slide rule" extensometer is attached for measuring creep strain and three Chromel-Alumel thermocouples are attached to the gage section for temperature measurements. Extensometer measurements were made visually through windows in the furnace by means of a filar micrometer microscope in which the smallest division equals 0.00005 inch.

The furnace was of conventional Chromel A wire wound design with taps along the side to allow for correcting small temperature differences. Furnace temperature was maintained to within ± 2F by Foxboro controllers in response to signals from the centrally located thermocouple. The temperature of a specimen under test was stabilized for at least 1/2 hour prior to loading.

For each temperature condition creep and stress-rupture data were obtained to 100 and 1000 hours using as many specimens as necessary to obtain precise information. The percent creep deformation obtained was dependent on the material under test. In most instances stress-time curves were defined for 0.2 and 0.5 percent elongation.

Stress Corrosion

Seven specimens of each alloy were tested for susceptibility to stress-corrosion cracking by alternate immersion in 3-1/2 percent sodium chloride solution at room temperature.

Specimens were prepared for testing by degreasing with acetone. Where a surface film remained from heat treating, it was abraded off one side and the adjacent long edge of five of the specimens, and left intact on the other two.

Each specimen was placed in a four-point loading fixture and deflected to a stress corresponding to 80 percent of the tensile yield strength of the particular material. The specimen was electrically insulated from the fixture by means of glass or sapphire rods. Deflection for a given maximum fiber stress was calculated by the following expression:

$$y = \frac{\sigma(3\ell^2 - 4a^2)}{12dE}$$

where

y = deflection

σ = maximum fiber stress

ℓ = distance between outer load points

a = distance between outer and inner load points

d = specimen thickness

E = modulus of specimen material

Each stressed specimen was suspended on an alternate immersion unit. This unit alternately immersed specimens in the 3.5 percent sodium chloride solution for ten minutes and held them above the solution to dry for 50 minutes. Tests were continued to the first sign of cracking or for 1000 hours, whichever occurred first.

Specimens were given frequent low-power microscopic examinations to detect cracks. At the first sign of cracking the specimen was removed. At the conclusion of the test, selected samples were sectioned and examined metallographically for any indication of cracking. Representative samples in which cracks were found were also given a metallographic examination to establish the type and extent of the cracks.

Thermal Expansion

Linear-thermal-expansion measurements were performed in a recording dilatometer with specimens protected by a vacuum of about 2 x 10^{-5} mm of mercury. In this apparatus a sheet-type specimen is supported between two graphite structures inside a tantalum-tube heater element. On heating, the differential movement of the two structures caused by specimen expansion results in the displacement of the core of a linear-variable differential transformer. The output of the transformer is recorded continuously as a function of specimen temperature. The entire assembly is enclosed in a vacuum chamber.

The furnace is controlled to heat at the desired rate, usually 5F per minute. Errors associated with measurements in this apparatus are estimated not to exceed ± 2 percent. This is based on calibration with materials of known thermal-expansion characteristics.

Fatigue

Two types of fatigue equipment were used to perform the axial-load tension fatigue tests. One type was the Krouse axial-load machine, either 5,000- or 10,000-pound capacity. The specific machine was dependent upon the test load requirements dictated by the product form and heat treatment. Fatigue tests on high-strength materials were conducted on the second type machine, namely, the MTS electrohydraulic-servocontrolled testing machine.

The Krouse axial-load equipment is mechanically driven and provides loads on a constant-deflection basis. These machines normally operate at 1725 cpm. Hydraulic load maintainers stabilize the mean load should some creep deformation occur.

The frequency at cycling of the MTS electrohydraulic fatigue machines is variable to beyond 2,000 cpm depending on specimen rigidity. These machines operate with closed-loop deflection, strain, or load control. Under load control used in this program, cyclic loads were automatically maintained (regardless of the required amount of ram travel) by means of load-cell feedback signals. The calibration and alignment of each machine are checked periodically. In each case, the dynamic load-control accuracy is better than ± 3 percent of the test load.

For elevated-temperature studies, electrical-resistance, wire-wound furnaces of conventional design were used to heat the specimens. Three Chromel-Alumel thermocouples, placed near the center of each specimen at 1 inch intervals, were employed in furnace calibration. During a fatigue test, the center thermocouple was used in conjunction with a Foxboro controller to adjust electrical input to the furnace. The thermal gradient along the test section was continuously monitored by the other two thermocouples. During tests, the center of the specimen was held to within ± 5 degrees of the control temperature.

After machining and heat treating (when required), the edges of all sheet and plate specimens were polished according to Battelle-Columbus' standard practice prior to testing. The unnotched specimens were held against a rotating drum covered with emery paper and polished using a kerosene lubricant. Successively finer grits of emery paper were used, as required, to produce a surface of about 10 rms. Unnotched round specimens were polished in the Battelle-Columbus polishing apparatus. This machine utilizes a rotating belt sander driven rectilinearly along the specimen test section while the specimen is being rotated. The belt speed and specimen speed are adjusted so that polishing marks on the specimen are in the longitudinal direction. The surface finish is about the same as that on the flat specimens. The notched flat specimens were held in a fixture and polished with a slurry of oil and alundum grit applied liberally to a rotating wire. Notched round specimens are polished in the same manner, except that the specimen is rotated.

A shadowgraph optical comparator was used for measuring the test sections of all polished specimens and for inspection of the root radius in the case of the notched specimens.

The stress ratio for all specimens was $R = 0.1$. Stresses for notched ($K_t = 3.0$) and unnotched specimens were selected so that S-N curves were defined between 10^3 and 10^7 cycles using approximately 10 specimens for each set of fatigue conditions.

Fracture Toughness

Two types of fracture toughness tests were used. For heavy section materials, the chevron-notched, slow bend test specimen of ASTM Method E-399-70T was selected. For thinner section sheet materials, center through-cracked tension panels were used as test specimens. All specimens were precracked in fatigue and subsequently fractured in a servocontrolled electrohydraulic testing system of appropriate load capacity.

The slow-bend type specimens were precracked and tested under 3-point loading. The pop-in load for materials susceptible to brittle fracture was determined from the load-compliance curve. When pop-in was not detectable, the curves were analyzed using the 5 percent secant offset method of the ASTM procedure.

The thin sheet center through-crack tension panels were initially sawcut and then precracked in constant amplitude fatigue loading. In order to maintain a flat fatigue crack and not plastically strain the uncracked section, the maximum stresses were adjusted to keep the applied stress-intensity factor less than one-third or one-quarter of that anticipated at fracture. This usually involved stepping down the stresses as the cracking proceeded. The crack was extended to approximately one-quarter of the panel width. Buckling guides were attached and a clip-type compliance gage was mounted in the central notch. The panels were fractured in a rising load test at a stress rate in the range

$$.002\ E < \dot{S} < .005\ E \text{ ksi/min} \quad ,$$

which corresponds nominally to the gross strain rate of standard tensile testing.

MATERIALS INFORMATION AND TEST RESULTS

Udimet 700 Alloy

Material Description

Udimet 700 is one of the older heat-resistant nickel-base alloys that has seen limited use in engines as forging and bar products. The Air Force has funded an intensive effort at Union Carbide Corporation to develop a sheet manufacturing process for this alloy. The material for this evaluation was supplied GFM from this effort. The development history and processing for the Udimet 700 sheet is contained in Reference (6).

The material tested was nominally 0.032-inch-thick sheet.

Processing and Heat Treating

The specimen layout for Udimet 700 sheet is shown in Figure 19. Specimens were machined in the as-received condition and heat-treated as follows:

2150 F for 2 hours with rapid air cool,

1950 F for 4 hours with air cool,

1550 F for 24 hours with air cool,

1400 F for 16 hours with air cool.

This heat treatment is designed to give the best stress-rupture properties while maintaining good mechanical properties.

Test Results

Tension. Results of tests in both the longitudinal and transverse directions at room temperature, 1000 F, 1400 F, and 1800 F are presented in Table I. Stress-strain curves at temperature are shown in Figure 20. Effect-of-temperature curves are shown in Figure 22.

Compression. Results of tests in the longitudinal and transverse directions are given in Table II for room temperature, 1000 F, 1400 F, and 1800 F. Compressive stress-strain and tangent-modulus curves at temperature are shown in Figure 21. Effect-of-temperature curves are shown in Figure 23.

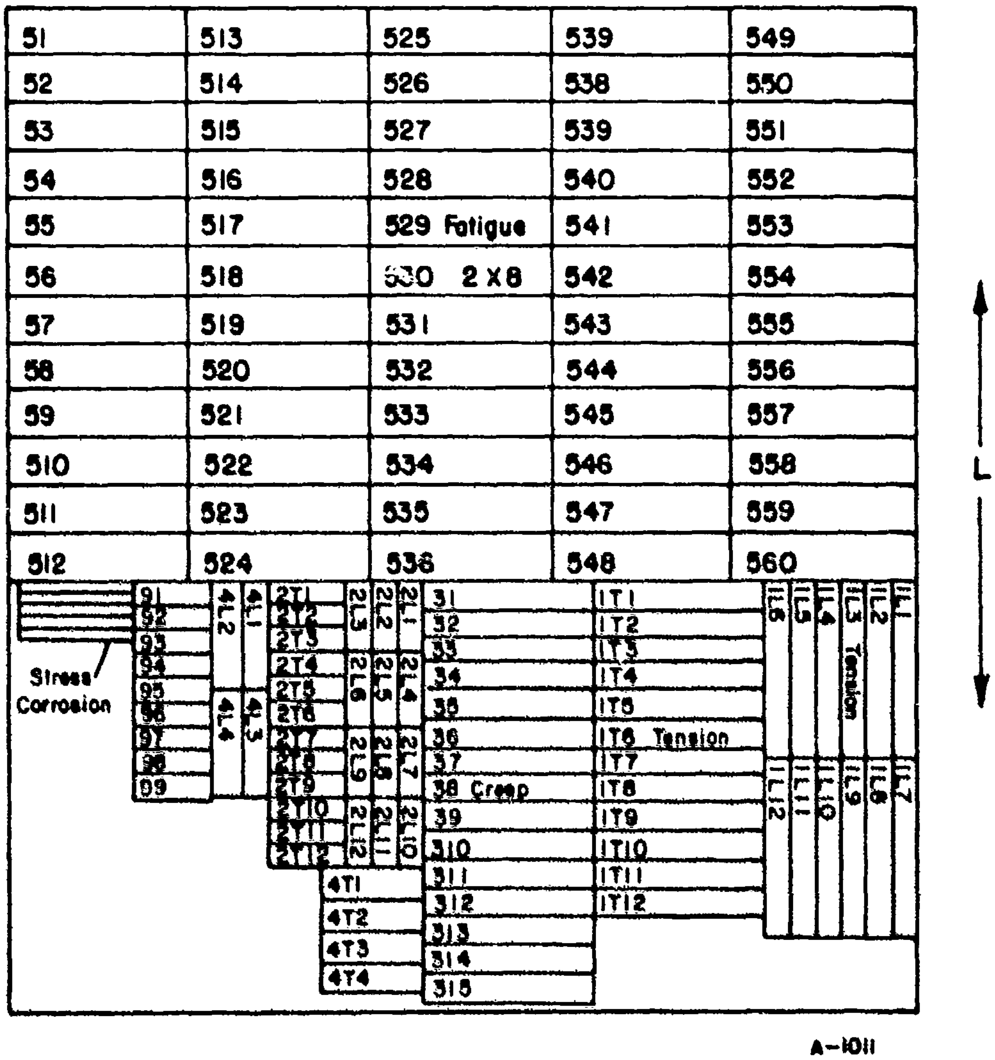


FIGURE 19. SPECIMEN LAYOUT FOR UDIMET-700 SHEET

Shear. Test results at room temperature for both the longitudinal and transverse directions are given in Table III.

Bend. Test results are given in the data sheet in the conclusions section of this report.

Fracture Toughness. Test specimens were the full sheet thickness (0.032 inch) x 18 inch x 48 inch with an EDM flaw in the center. The average K_c value obtained was 210 ksi$\sqrt{in.}$ The net section yield stress at fracture was less than the tensile yield strength of the material. Therefore, the K_c value is considered valid.

Fatigue. Axial-load tests were conducted at room temperature, 1000 F, and 1400 F for unnotched and notched transverse specimens. Test results are presented in Tables IV and V. S-N curves are shown in Figures 24 and 25.

Creep and Stress Rupture. Tests were conducted at 1000 F, 1400 F, and 1800 F. Results are presented in tabular form in Table VI and as log stress-versus-log time in Figure 26.

Stress Corrosion. Specimens were tested as described in the experimental procedure section of this report. No failures or cracks occurred in the 1000-hour test duration.

Thermal Expansion and Density. Values obtained are given in the "data sheet" in the conclusions section of this report.

TABLE I. TENSION TEST RESULTS FOR UDIMET 700 SHEET

Specimen No.	Ultimate Tensile Strength, ksi	0.2 Percent Offset Yield Strength, ksi	Elongation in 2 inches, percent	Tensile Modulus, psi x 10^6
		Longitudinal at Room Temperature		
1L1	224.0	150.0	22.0	32.6
1L2	224.0	150.0	22.0	32.4
1L3	226.0	151.0	21.0	33.7
		Transverse at Room Temperature		
1T1	214.0	150.0	20.0	34.0
1T2	213.0	150.0	21.0	33.4
1T3	214.0	150.0	22.0	34.9
		Longitudinal at 1000 F		
1L4	214.0	141.0	16.0	30.4
1L5	213.0	139.0	16.0	28.4
1L6	212.0	139.0	15.0	28.5
		Transverse at 1000 F		
1T4	199.0	138.0	16.0	34.6
1T5	201.0	138.0	18.0	30.5
1T6	199.0	139.0	15.0	30.0
		Longitudinal at 1400 F		
1L7	128.0	122.0	35.0	23.4
1L8	127.0	121.0	35.0	22.7
1L9	127.0	121.0	34.0	23.4
		Transverse at 1400 F		
1T7	127.0	124.5	25.0	24.8
1T8	128.0	125.0	25.0	25.1
1T9	128.0	125.0	30.0	25.4

TABLE I. (Concluded)

Specimen No.	Ultimate Tensile Strength, ksi	0.2 Percent Offset Yield Strength, ksi	Elongation in 2 inches, percent	Tensile Modulus, psi x 10^6
		Longitudinal at 1800 F		
1L10	26.5	22.7	50.0	(a)
1L11	26.9	22.7	48.0	12.7
1L12	27.4	23.1	36.0	14.0
		Transverse at 1800 F		
1T10	26.4	22.2	36.0	14.9
1T11	27.1	23.3	35.0	(a)
1T12	27.2	23.2	38.0	12.5

(a) Load-strain curve not suitable for modulus determination.

TABLE II. COMPRESSION TEST RESULTS FOR UDIMET 700 SHEET

Specimen No.	0.2 Percent Offset Yield Strength, ksi	Compression Modulus, psi x 10^6
Longitudinal at Room Temperature		
2L1	160.0	34.7
2L2	160.0	33.1
2L3	162.0	32.8
Transverse at Room Temperature		
2T1	157.0	36.6
2T2	163.0	35.4
2T3	163.0	36.2
Longitudinal at 1000 F		
2L4	142.0	28.8
2L5	149.0	30.7
2L6	149.0	33.6
Transverse at 1000 F		
2T4	145.0	32.1
2T5	148.0	35.1
2T6	150.0	31.6
Longitudinal at 1400 F		
2L7	123.0	23.9
2L8	126.0	23.9
2L9	126.0	25.1
Transverse at 1400 F		
2T7	123.0	24.9
2T8	125.0	26.1
2T9	127.0	22.8

TABLE II. (Concluded)

Specimen No.	0.2 Percent Offset Yield Strength, ksi	Compression Modulus, psi x 10^6
	Longitudinal at 1800 F	
2L10	21.6	12.6
2L11	21.8	12.4
2L12	21.6	11.9
	Transverse at 1800 F	
2T10	(a)	(a)
2T11	22.2	11.6
2T12	20.8	11.6

(a) Machine malfunction.

TABLE III. SHEAR TEST RESULTS FOR UDIMET 700 SHEET AT ROOM TEMPERATURE

Specimen No.	Ultimate Shear Strength, ksi
	<u>Longitudinal</u>
4L1	144.0
4L2	145.0
4L3	142.0
4L4	142.0
	<u>Transverse</u>
4T1	150.0
4T2	149.0
4T3	(a)
4T4	145.0

(a) Did not fail in shear.

TABLE IV. AXIAL-LOAD FATIGUE TEST RESULTS FOR UNNOTCHED UDIMET 700 SHEET AT A STRESS RATIO OF R = 0.1

Specimen No.	Maximum Stress, ksi	Lifetime, cycles
	Room Temperature	
543	200	8
544	180	24,926
545	160	71,159
540	140	168,024
541	120	342,670
542	110	525,300
539	100	847,200
538	90	1,418,800
537	80	10,075,600[a]
	1000 F	
558	180	8,700
556	170	8,200
550	160	15,200
549	150	15,600
551	140	1,837,100
548	120	10,024,800[a]
	1400 F	
553	160	9,700
531	150	2,900
554	140	105,200
532	130	1,304,100
555	120	439,500
546	110	2,673,100
557	100	6,484,000
552	90	14,000,100[a]

(a) Did not fail.

TABLE V. AXIAL-LOAD FATIGUE TEST RESULTS FOR NOTCHED (K_t = 3.0) UDIMET 700 SHEET AT A STRESS RATIO OF R = 0.1

Specimen No.	Maximum Stress, ksi	Lifetime, cycles
	Room Temperature	
530	140	7,800
529	130	13,300
528	120	15,300
526	110	16,400
527	90	35,400
524	80	84,700
525	70	166,700
523	60	217,300
522	50	533,200
521	40	10,028,500 [(a)]
	1000 F	
517	130	2,700
520	120	4,700
512	110	6,900
519	100	8,700
511	90	14,100
513	85	32,800
516	80	29,200
53	60	2,040,000
510	50	11,583,100 [(a)]
	1400 F	
56	90	4,700
514	80	9,900
57	75	56,700
51	70	287,800
58	65	562,200
552	60	14,567,900 [(a)]

(a) Did not fail

TABLE VI. SUMMARY DATA ON CREEP AND RUPTURE PROPERTIES OF UDIMET 700 SHEET

Specimen No.	Stress, ksi	Temp, F	Hours to Indicated Creep Deformation, percent					Initial Strain, percent	Rupture Time, hr	Elongation in 2 Inches, percent	Minimum Creep Rate, percent/hr
			0.1	0.2	0.5	1.0	2.0				
U-316	199.0	1000	--	--	--	--	--	--	On loading	12.4	--
U-317	190.0	1000	0.01	0.05	0.15	0.4	1.5	12.12	8.3	21.3	0.58
U-312	180.0	1000	0.1	0.2	0.6	2.5	10.0	8.60	100.6	20.0	0.08
U-37	160.0	1000	0.4	2.0	18.0	165.0	925.0	4.102	604.5(2)	5.69	0.0012
U-314	135.0	1000	2000.0(1)	7500.0(1)	--	--	--	0.496	626.7(2)	0.571	0.000018
U-313	120.0	1000	--	--	--	--	--	0.386	456.4(2)	0.422	--
U-38	80.0	1400	0.3	0.7	1.8	3.7	7.5	0.147	13.3	8.0	0.24
U-36	70.0	1400	1.4	3.0	9.0	16.5	27.0	0.149	53.4	11.6	0.050
U-39	52.0	1400	10.0	20.0	47.0	80.0	130.0	0.145	248.3	13.3	0.009
U-310	35.0	1400	32.0	84.0	237.0	425.0	657.0	0.078	1317.0	15.6	0.0017
U-315	20.0	1400	185.0	440.0	1160.0(1)	2400.0(1)	--	0.062	407.5(2)	0.255	0.0004
U-31	15.0	1800	0.02	0.04	0.08	0.16	0.33	0.251	1.4	26.7	6.0
U-32	10.0	1800	0.04	0.10	0.20	0.40	0.85	0.193	5.0	27.1	2.0
U-33	4.0	1800	0.13	0.6	1.7	3.6	7.6	0.018	56.5	39.6	0.26
U-35	1.6	1800	2.1	5.0	13.0	25.0	44.0	0.029	838.4	122.7	0.040
U-311	0.4	1800	100.0	145.0	292.0	585.0	1100.0(1)	0	413.7(2)	0.685	0.0020

(1) Estimated.
(2) Test discontinued.

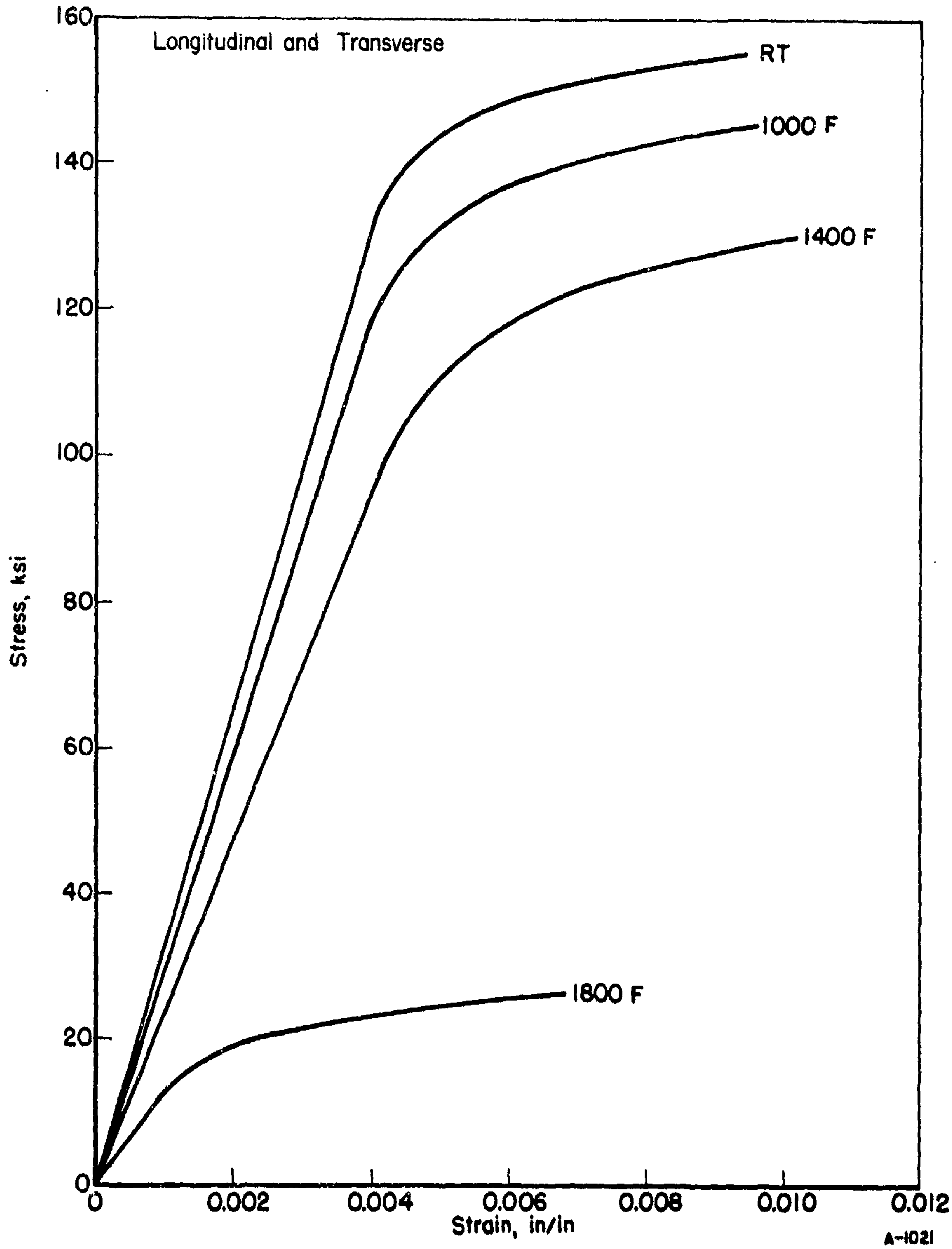


FIGURE 20. TYPICAL STRESS-STRAIN CURVES FOR UDIMET-700 SHEET (LONGITUDINAL AND TRANSVERSE)

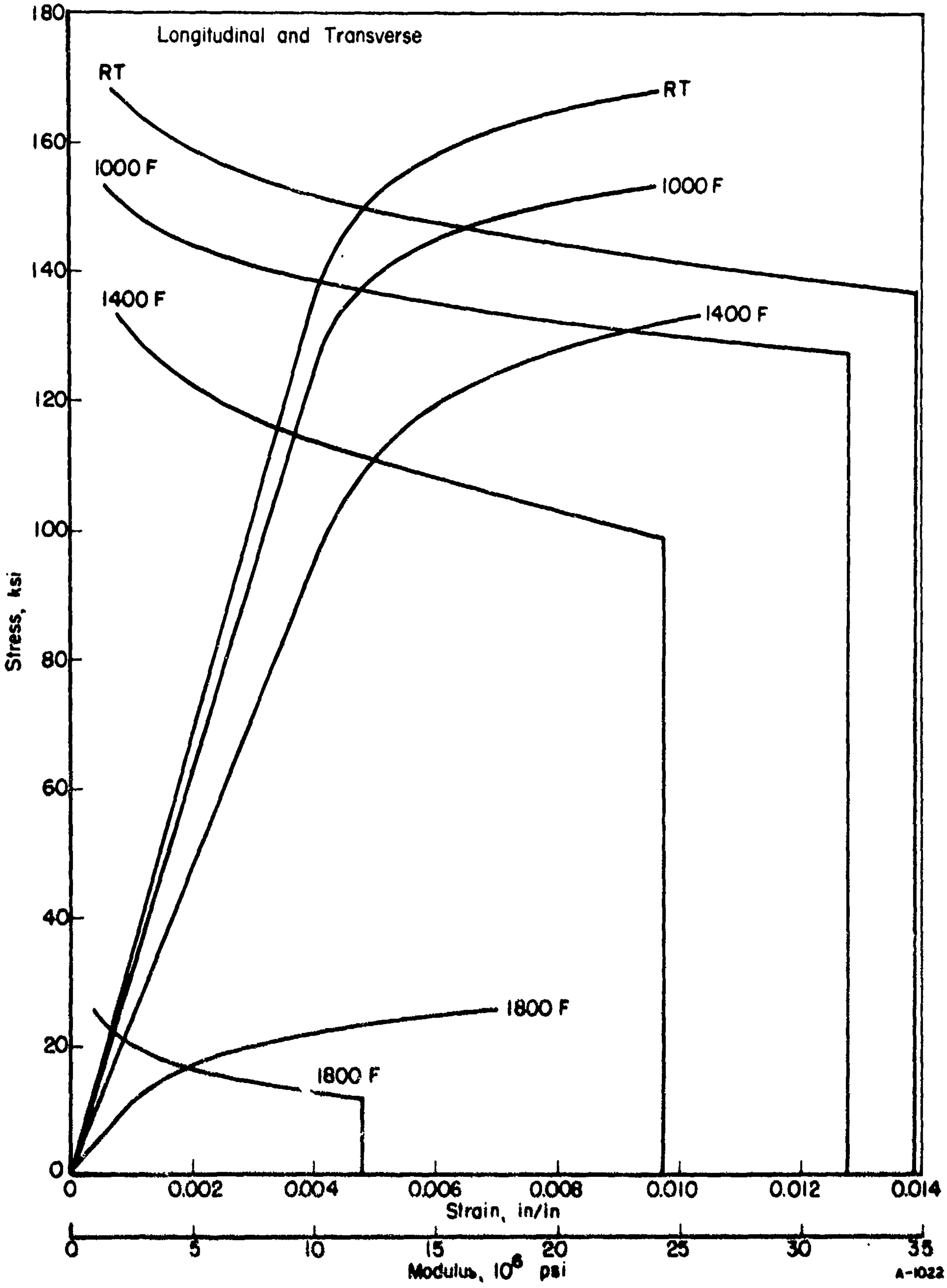


FIGURE 21. TYPICAL COMPRESSIVE STRESS-STRAIN AND TANGENT MODULUS CURVES FOR UDIMET-700 SHEET (LONGITUDINAL AND TRANSVERSE)

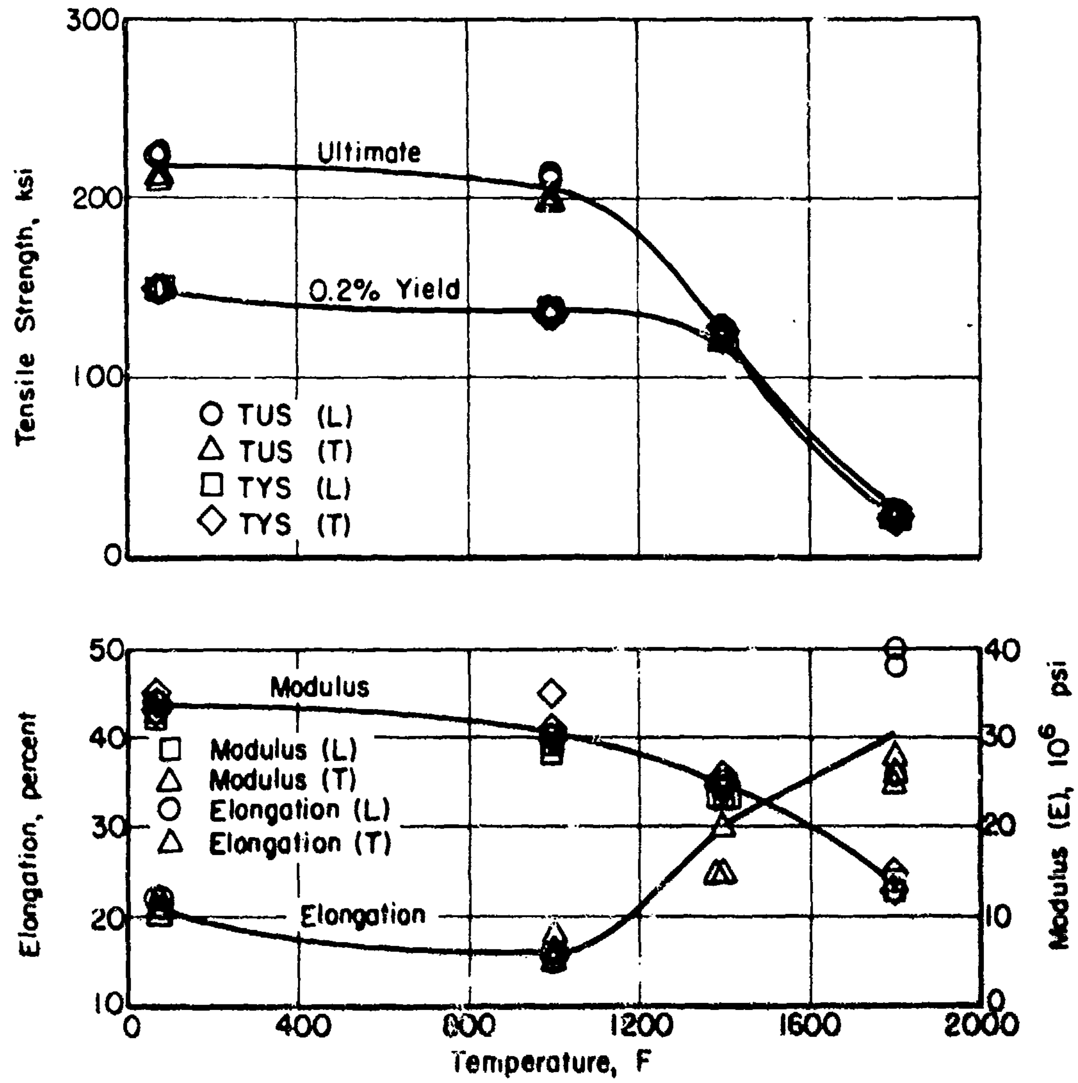


FIGURE 22. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF UDIMET-700 SHEET

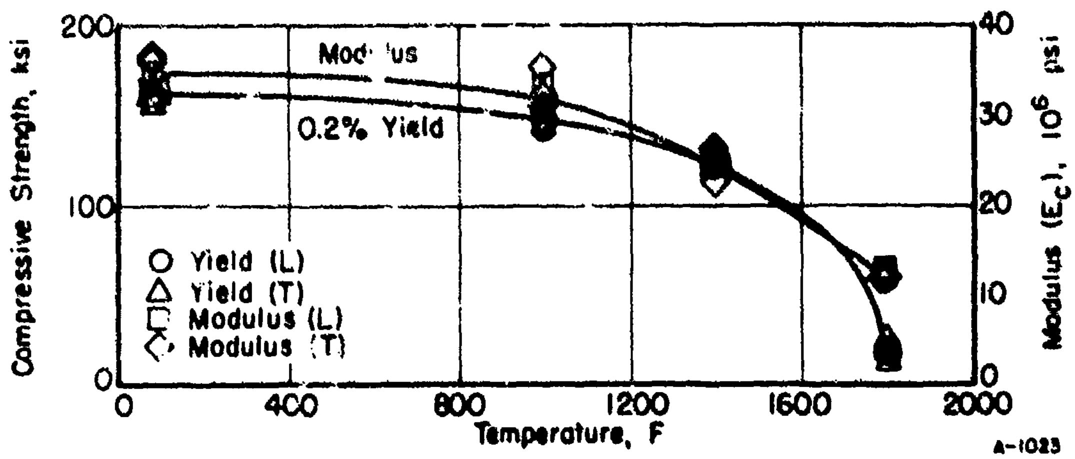


FIGURE 23. EFFECT OF TEMPERATURE ON THE COMPRESSIVE PROPERTIES OF UDIMET-700 SHEET

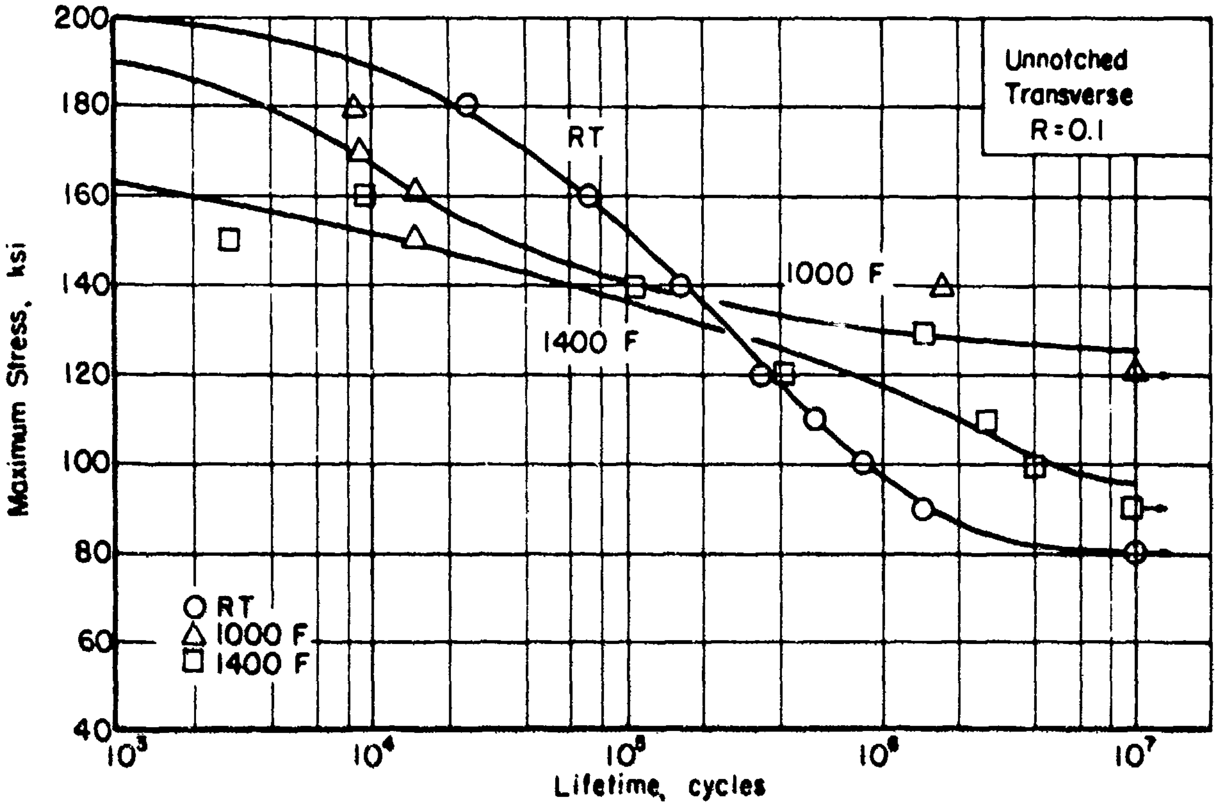


FIGURE 24. AXIAL-LOAD FATIGUE RESULTS FOR UDIMET-700 SHEET

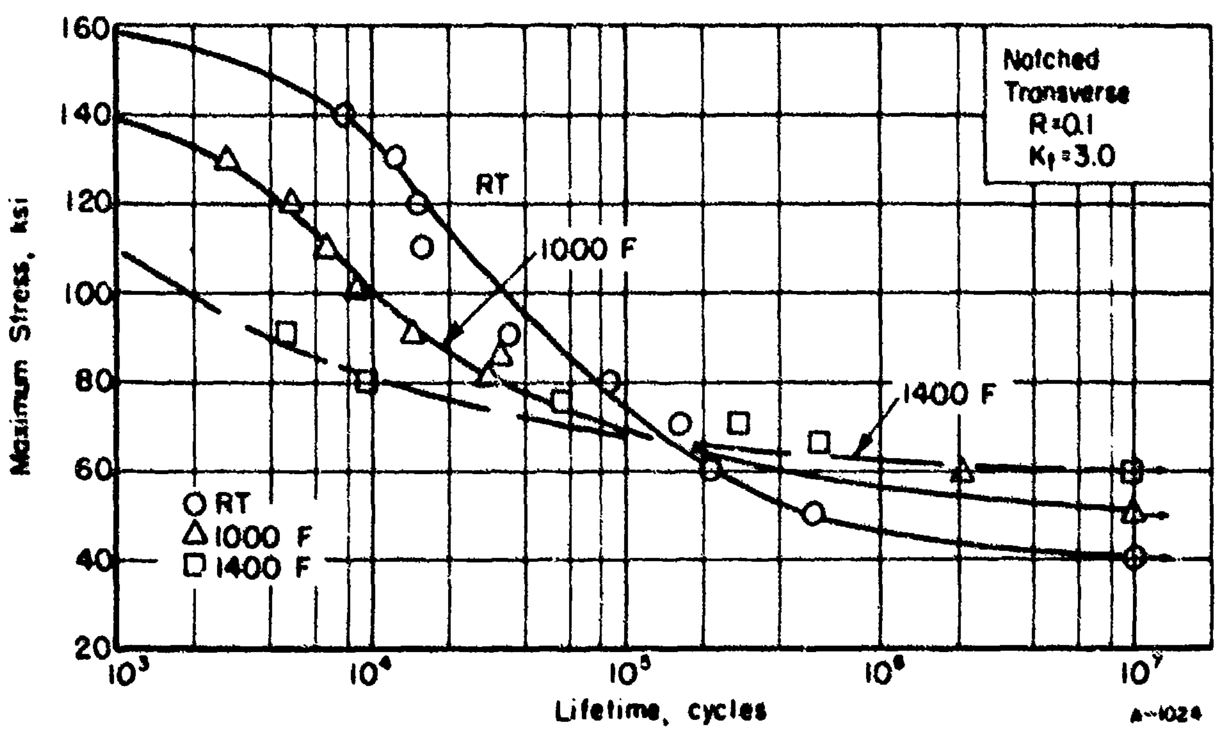


FIGURE 25. AXIAL-LOAD FATIGUE RESULTS FOR NOTCHED (K_t=3.0) UDIMET-700 SHEET

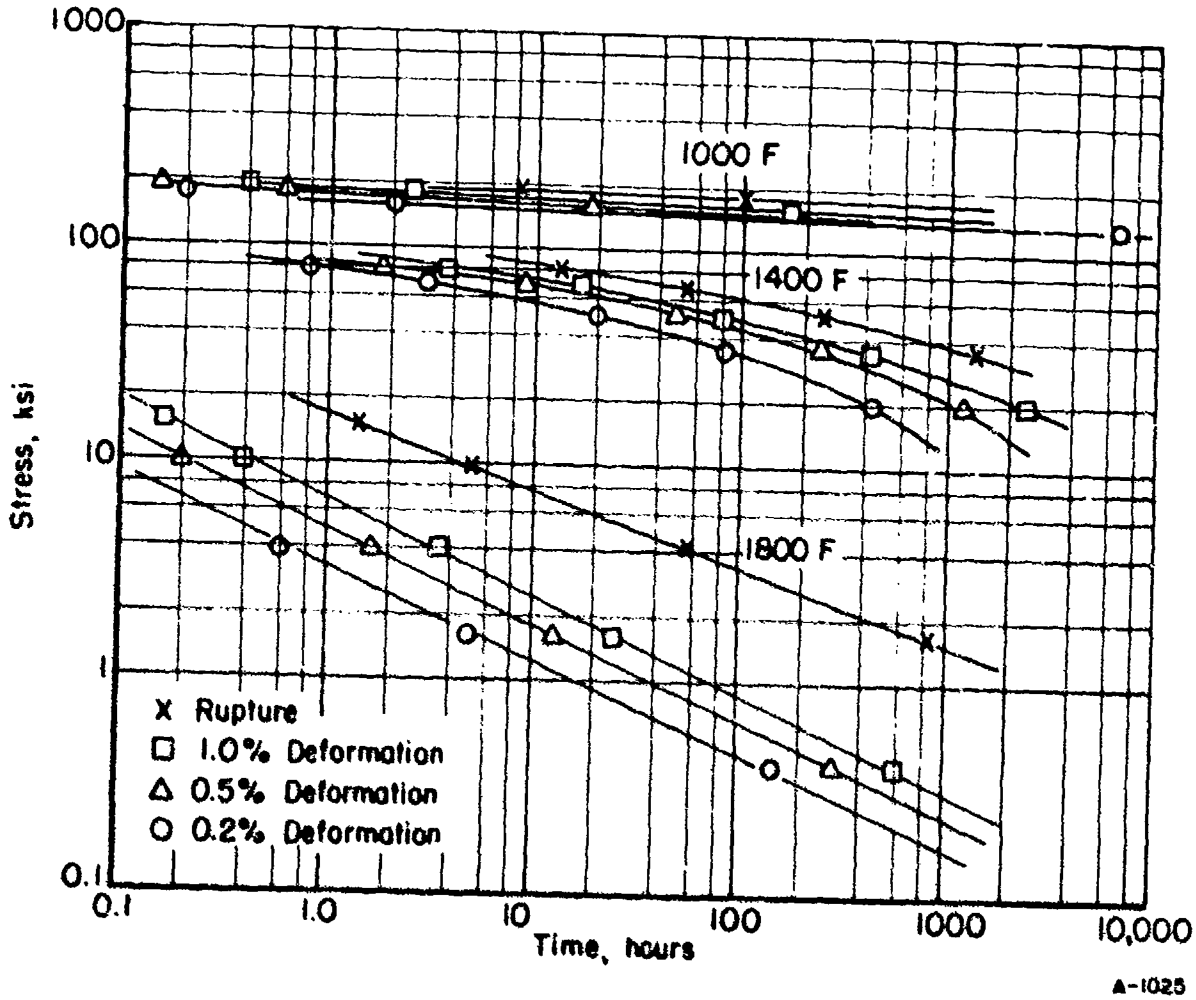


FIGURE 26. STRESS-RUPTURE AND PLASTIC DEFORMATION CURVES FOR UDIMET-700 SHEET

X5090 Alloy

Material Description

Alloy X5090 is a recent development of the Aluminum Division, Olin Corporation. As a basic aluminum-7% magnesium alloy, it is designed to offer exceptional mechanical properties in the cold-worked and stabilized temper without susceptibility to stress-corrosion cracking. A combination of controlled chemistry of minor elements and controlled thermal processing has resulted in light gage, full-hard sheet materials with mechanical properties in excess of those of 2024-T3. The alloy, as reported by Olin, is characterized by low density, excellent fracture toughness, excellent fatigue strength, and excellent general corrosion resistance, as well as freedom from susceptibility to stress-corrosion cracking.

Composition limits of this alloy are as follows:

Chemical Composition	Percent
Silicon	0.50 max
Iron	0.50 max
Copper	0.25 max
Manganese	0.35 max
Magnesium	6.0 to 8.0
Chromium	0.05 to 0.30
Zinc	0.20 max
Titanium	0.015 max
Beryllium	0.001 to 0.002
Boron	0.001 to 0.050
Others	0.15 max
Aluminum	balance

The material was obtained as 0.025-inch x 38-inch x 96-inch sheet.

Processing and Heat Treating

The specimen layout for X5090 alloy is presented in Figure 27. Specimens were tested in the 75 percent cold-rolled and stabilized -H38 condition.

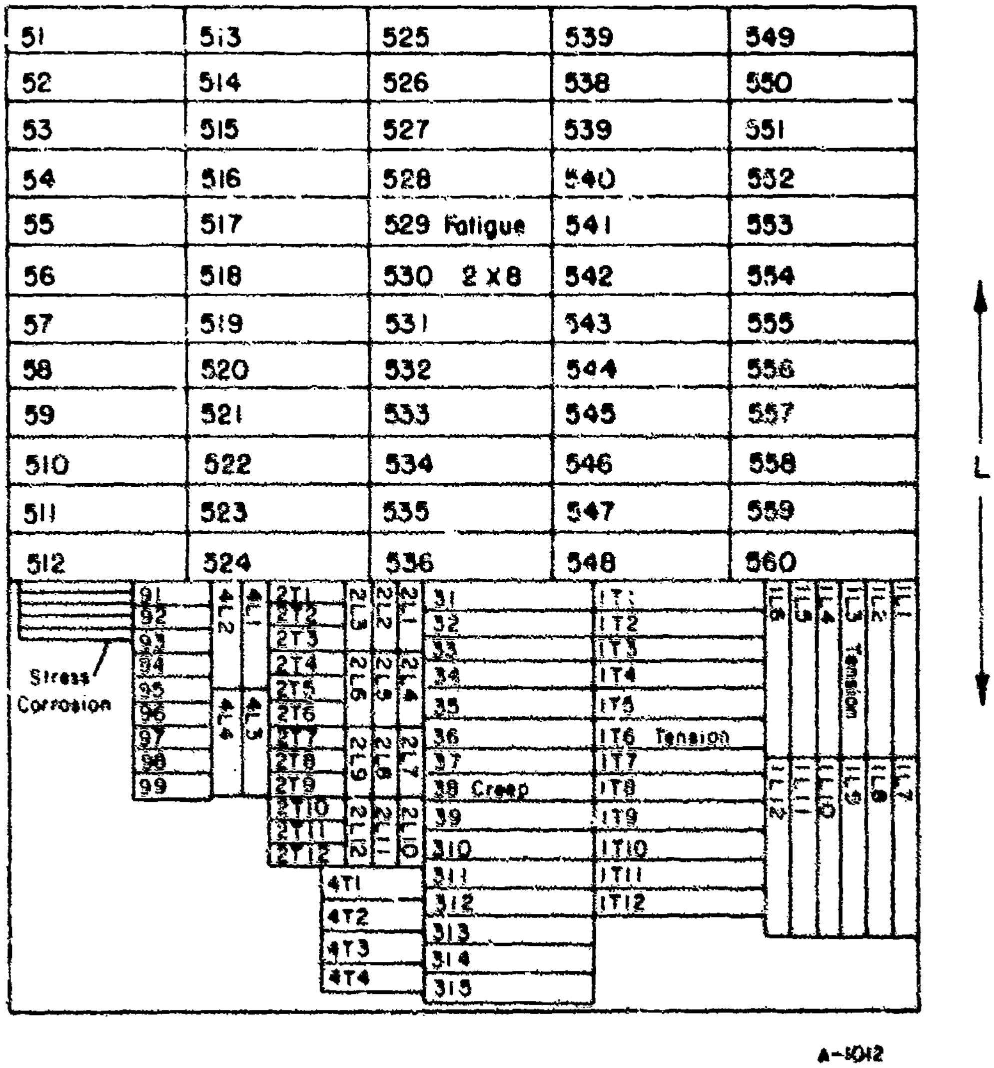


FIGURE 27. SPECIMEN LAYOUT FOR X5090 ALUMINUM SHEET

Test Results

Tension. Results of tests in both the longitudinal and transverse directions at room temperature, 200 F, 325 F, and 400 F are presented in Table VII. Stress-strain curves at temperature are shown in Figures 28 and 29. Effect-of-temperature curves are shown in Figure 32.

Compression. Results of tests at room temperature, 200 F, 325 F, and 400 F for both the longitudinal and transverse directions are given in Table VIII. Compressive stress-strain and tangent-modulus curves are presented in Figures 30 and 31. Effect-of-temperature curves are shown in Figure 33.

Shear. Results of room-temperature tests in the longitudinal and transverse directions are given in Table IX.

Bend. Results of bend tests show the minimum bend radius to be about 4t in the longitudinal direction and 3.5t in the transverse direction.

Fracture Toughness. Test specimens were sheet thickness x 18 inch x 48 inch with an EDM flaw in the center. The average K_c obtained was 49 ksi$\sqrt{\text{in.}}$ The net section yield stress at fracture was less than the tensile yield strength of the material. Therefore, the K_c values are considered valid.

Fatigue. Axial-load tests were conducted at room temperature, 200 F, and 325 F for transverse specimens, both unnotched and notched. Tabular test results are presented in Tables X and XI. S-N curves are shown in Figures 34 and 35.

Creep and Stress Rupture. Results of transverse tests at 200 F, 325 F, and 400 F are given in tabular form in Table XII. Log stress-versus-log time curves are shown in Figure 36.

Stress Corrosion. Specimens were tested as described in the experimental procedure section of this report. No failures or cracks occurred in the 1000-hour test duration.

Thermal Expansion and Density. Values obtained are given in the "data sheet" in the conclusions section of this report.

TABLE VII. TENSION TEST RESULTS FOR X5090 ALUMINUM SHEET

Specimen No.	Ultimate Tensile Strength, ksi	0.2 Percent Offset Yield Strength, ksi	Elongation in 2 Inches, percent	Tensile Modulus, psi x 10^6
		Longitudinal at Room Temperature		
1L1	73.5	58.4	6.0	12.5
1L2	75.1	59.2	8.0	12.8
1L3	73.1	58.4	6.5	13.4
		Transverse at Room Temperature		
1T1	72.6	52.6	10.0	10.5
1T2	72.0	52.6	9.0	10.4
1T3	72.4	53.2	8.0	10.6
		Longitudinal at 200 F		
1L4	62.2[a]	54.1	11.5	9.4
1L5	62.4[a]	54.8	12.0	9.2
1L6	63.3[a]	54.8	15.5	9.5
		Transverse at 200 F		
1T4	61.8	50.6	20.0	9.4
1T5	62.3	50.9	21.0	9.2
1T6	61.8	50.6	22.0	9.7
		Longitudinal at 325 F		
1L7	35.4	30.7	39.0	7.0
1L8	35.9	30.1	50.0	7.2
1L9	36.5	30.8	52.0	7.2
		Transverse at 325 F		
1T7	41.1	36.9	42.0	7.5
1T8	41.8	38.3	39.0	7.7
1T9	41.7	37.7	36.0	7.3

TABLE VII. (Concluded)

Specimen No.	Ultimate Tensile Strength, ksi	0.2 Percent Offset Yield Strength, ksi	Elongation in 2 Inches, percent	Tensile Modulus, psi x 10^6
		Longitudinal at 400 F		
1L10	18.9	12.7	84.0	(b)
1L11	19.3	12.8	82.0	4.8
1L12	19.4	14.5	72.0	4.2
		Transverse at 400 F		
1T10	22.8	19.6	38.0	5.6
1T11	23.4	20.6	56.0	5.0
1T12	22.4	19.6	54.0	4.8

(a) Failed under knife edge.

(b) Load strain curve not suitable for modulus determination.

TABLE VIII. COMPRESSION TEST RESULTS FOR X5090 ALUMINUM SHEET

Specimen No.	0.2 Percent Offset Yield Strength, ksi	Compression Modulus, psi x 10^6
Longitudinal at Room Temperature		
2L1	57.4	10.6
2L2	57.4	10.5
2L3	57.6	10.5
Transverse at Room Temperature		
2T1	62.8	10.8
2T2	63.8	10.7
2T3	64.0	10.7
Longitudinal at 200 F		
2L4	57.1	10.6
2L5	57.8	10.5
2L6	59.0	10.8
Transverse at 200 F		
2T4	65.0	11.2
2T5	67.6	11.1
2T6	65.7	11.3
Longitudinal at 325 F		
2L7	40.6	7.8
2L8	42.6	7.9
2L9	41.5	8.5
Transverse at 325 F		
2T7	46.2	8.2
2T8	48.3	8.3
2T9	46.5	8.0

TABLE VIII. (Concluded)

Specimen No.	0.2 Percent Offset Yield Strength, ksi	Compression Modulus, psi x 10^6
	Longitudinal at 400 F	
2L10	18.1	7.1
2L11	20.6	6.8
2L12	18.7	6.6
	Transverse at 400 F	
2T10	29.9	6.8
2T11	29.9	6.4
2T12	27.8	6.8

TABLE IX. SHEAR TEST RESULTS FOR X5090 ALUMINUM SHEET AT ROOM TEMPERATURE

Specimen No.	Ultimate Shear Strength, ksi
	<u>Longitudinal</u>
4L1	42.9
4L2	42.9
4L3	43.0
4L4	43.1
	<u>Transverse</u>
4T1	41.9
4T2	41.9
4T3	41.9
4T4	41.9

TABLE X. AXIAL LOAD FATIGUE TEST RESULTS FOR UNNOTCHED X5090 ALUMINUM SHEET AT A STRESS RATIO OF R = 0.1

Specimen No.	Maximum Stress, ksi	Lifetime, cycles
	Room Temperature	
5-56	80.0	5
5-52	70.0	7,562
5-55	60.0	21,289
5-51	50.0	39,210
5-53	40.0	112,340
5-57	35.0	4,731,010
5-54	30.0	10,050,800[a]
	200 F	
5-50	60.0	40
5-49	60.0	440
5-46	55.0	4,520
5-48	50.0	19,670
5-42	45.0	28,440
5-36	40.0	112,560
5-43	35.0	58,390
5-44	30.0	1,052,540
5-45	27.5	1,743,190
5-37	35.0	15,533,200[a]
	325 F	
5-31	50.0	30
5-35	50.0	50
5-33	45.0	12,540
5-32	40.0	21,460
5-38	35.0	63,110
5-34	30.0	96,460
5-41	25.0	507,670
5-39	20.0	791,900
5-40	15.0	10,624,100[a]

(a) Did not fail.

TABLE XI. AXIAL-LOAD FATIGUE TEST RESULTS FOR NOTCHED (K_t = 3.0) X5090 ALUMINUM SHEET AT A STRESS RATIO OF R = 0.1

Specimen No.	Maximum Stress, ksi	Lifetime, cycles
	Room Temperature	
5-29	50.0	1,200
5-30	40.0	4,860
5-25	35.0	8,400
5-28	30.0	40,720
5-27	25.0	8,210
5-24	25.0	24,310
5-26	20.0	2,040,540
5-13	20.0	8,278,900
5-17	15.0	4,468,480
	200 F	
5-19	45.0	1,600
5-14	40.0	3,510
5-21	35.0	7,080
5-40	30.0	12,150
5-20	25.0	27,057
5-23	20.0	58,120
5-22	15.0	387,540
5-12	12.5	12,158,200[(a)]
5-18	10.0	16,671,360[(a)]
	325 F	
5-10	40.0	750
5-9	35.0	1,650
5-11	30.0	4,450
5-8	25.0	8,960
5-15	20.0	20,000
5-6	15.0	62,460
5-5	10.0	492,860
5-1	5.0	10,003,400[(a)]

(a) Did not fail.

TABLE XII. SUMMARY DATA ON CREEP AND RUPTURE PROPERTIES OF X-5090 ALUMINUM SHEET

Specimen No.	Stress, ksi	Temp, F	Hours to Indicated Creep Deformation, percent					Initial Strain, percent	Rupture Time, hr	Elongation in 2 Inches, percent	Minimum Creep Rate, percent/hr
			0.1	0.2	0.5	1.0	2.0				
3-2	50.0	200	0.1	0.25	1.0	2.7	4.5	0.774	20.8	24.9	0.27
3-1	40.0	200	0.75	2.2	10.0	26.0	53.0	0.418	204.7	28.0	0.035
3-4	34.5	200	2.2	6.3	25.0	85.0	142.0	0.356	580.6	29.8	0.014
3-7	25.0	200	4.5	10.0	90.0	235.0	520.0 (a)	0.225	455.2 (b)	1.986	0.0034
3-11	15.0	200	20.0	102.0	515.0	1300.0 (a)	2100.0 (a)	0.224	529.7 (b)	0.742	0.00064
3-13	[illegible]	200	70.0	460.0	1850.0 (a)	--	--	0.125	523.2 (b)	0.342	0.00020
3-9	25.0	325	0.02	0.06	0.18	0.4	0.9	0.366	5.0	37.8	2.0
3-8	15.0	325	0.2	0.6	1.6	4.5	13.0	0.118	88.6	27.6	0.12
3-10	10.0	325	0.6	1.8	9.0	40.0	197.0	0.016	1307.1	28.9	0.0050
3-14	7.0	325	70.0	260.0	1100.0 (a)	--	--	0.013	335.4 (b)	0.233	0.0004
3-5	10.0	400	0.04	0.10	0.3	0.7	1.4	0.338	12.7	29.0	1.3
3-3	7.0	400	0.2	0.45	1.7	4.4	11.0	0.215	91.5	41.3	0.15
3-6	4.5	400	0.6	2.0	16.0	46.0	160.0	0.186	979.3	28.0	0.0086
3-12	1.5	400	100.0	335.0	3000.0 (a)	--	--	0.011	695.3 (b)	0.251	0.00010

(a) Estimate.
(b) Test discontinued.

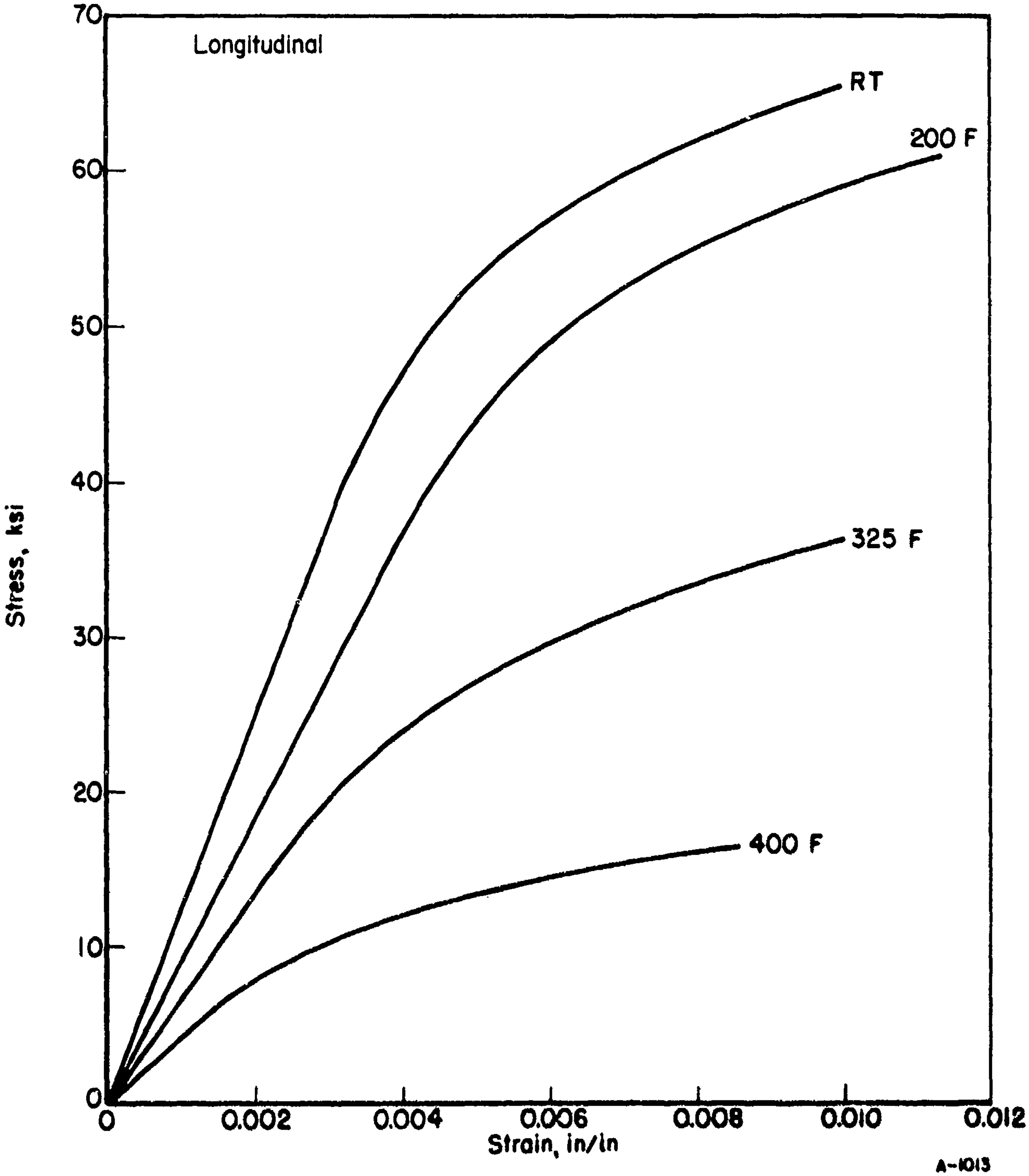


FIGURE 28. TYPICAL STRESS-STRAIN CURVES FOR X-5090 ALUMINUM SHEET (LONGITUDINAL)

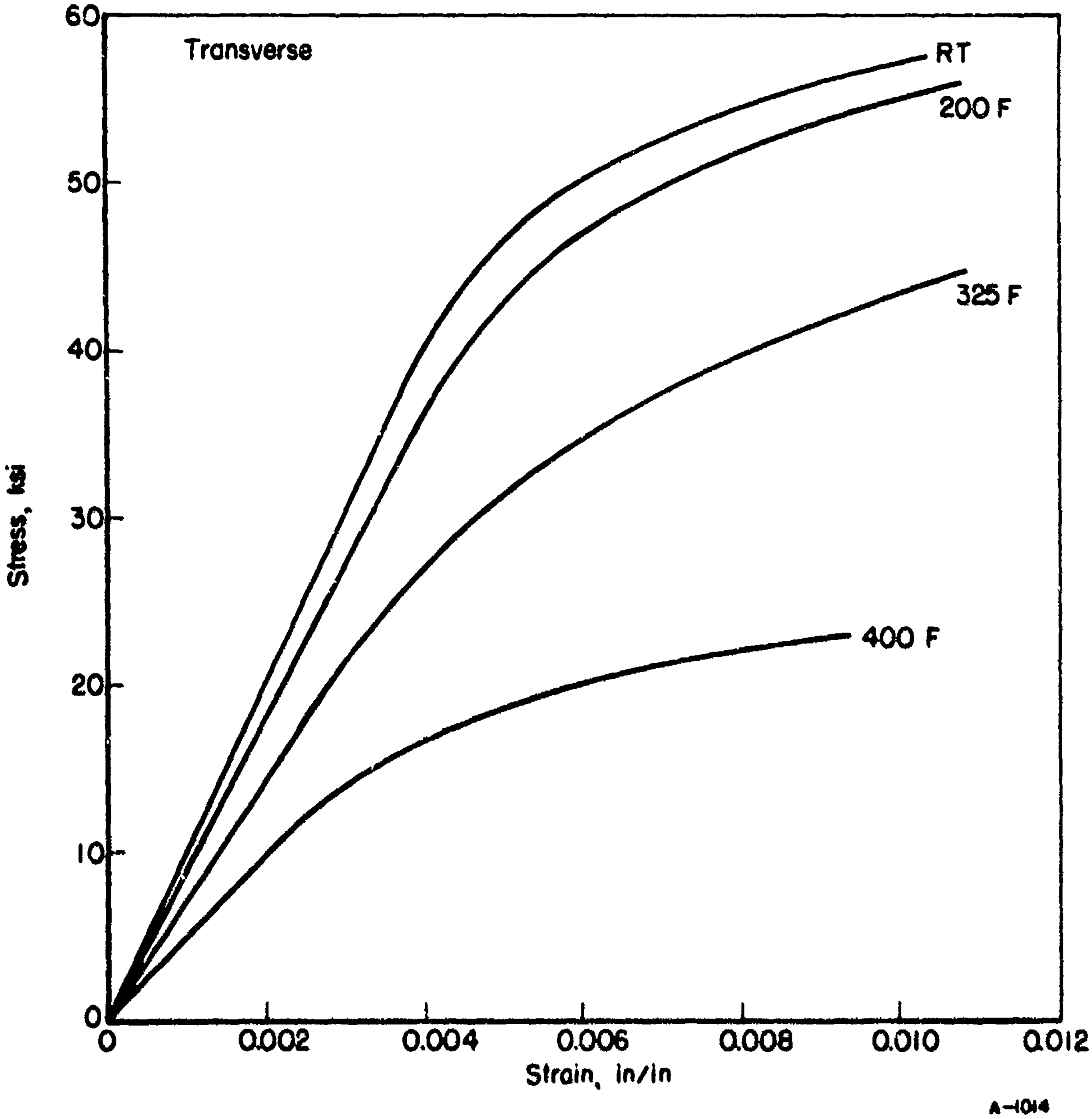


FIGURE 29. TYPICAL STRESS-STRAIN CURVES FOR X-5090 ALUMINUM SHEET (TRANSVERSE)

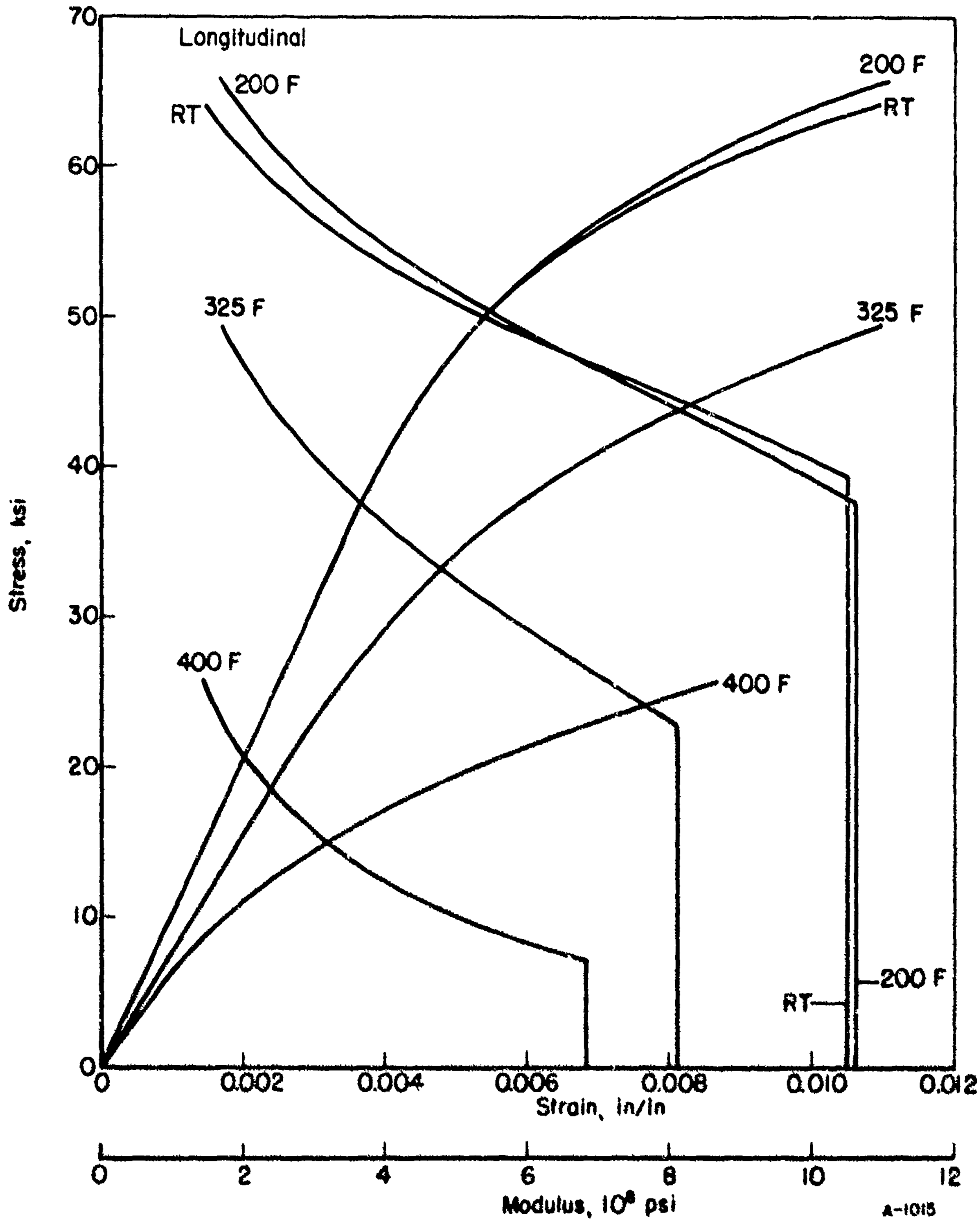


FIGURE 30. TYPICAL COMPRESSIVE STRESS-STRAIN AND TANGENT MODULUS CURVES FOR X-5090 ALUMINUM SHEET (LONGITUDINAL)

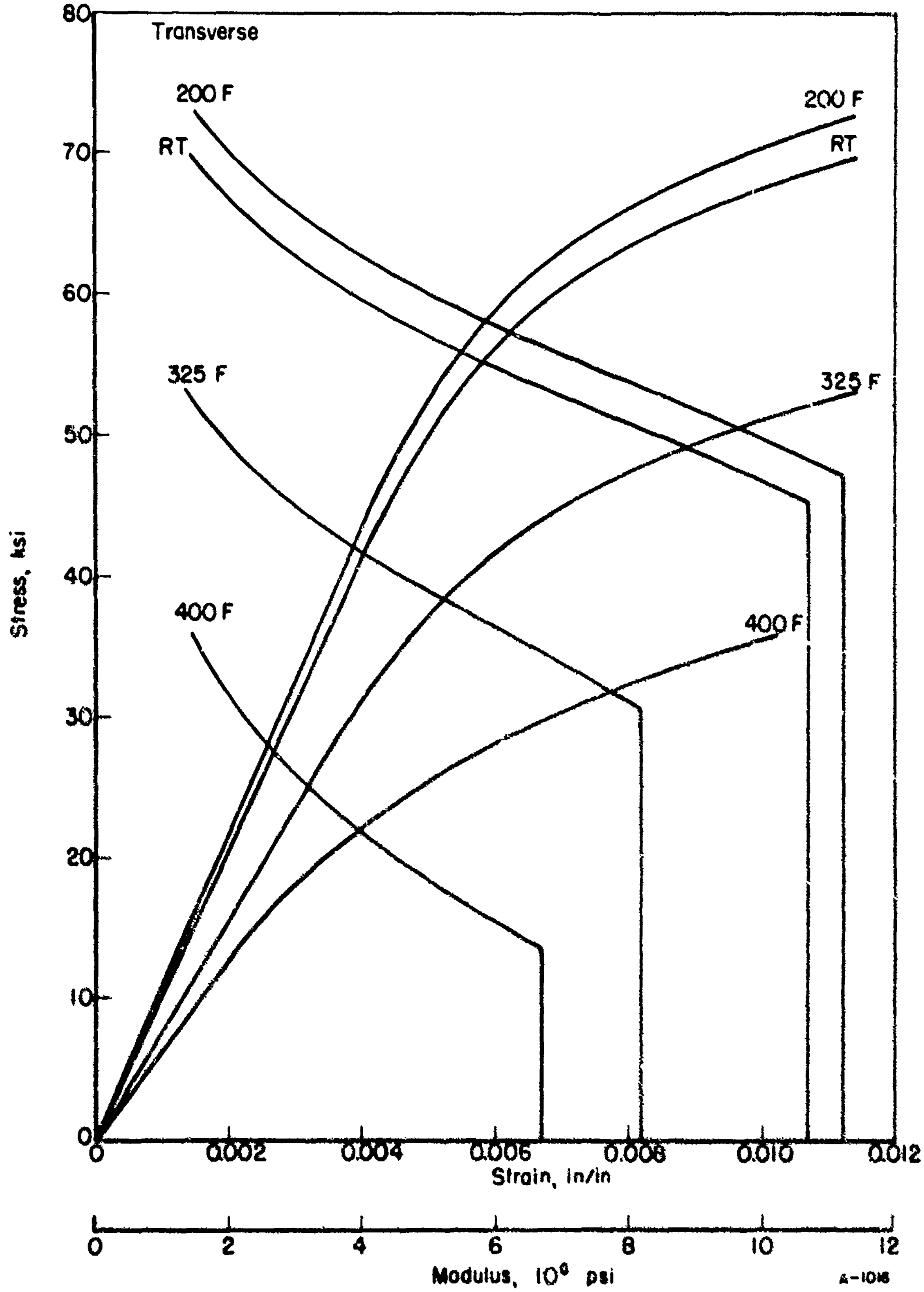


FIGURE 31. TYPICAL COMPRESSIVE STRESS-STRAIN AND TANGENT MODULUS CURVES FOR X-5090 ALUMINUM SHEET (TRANSVERSE)

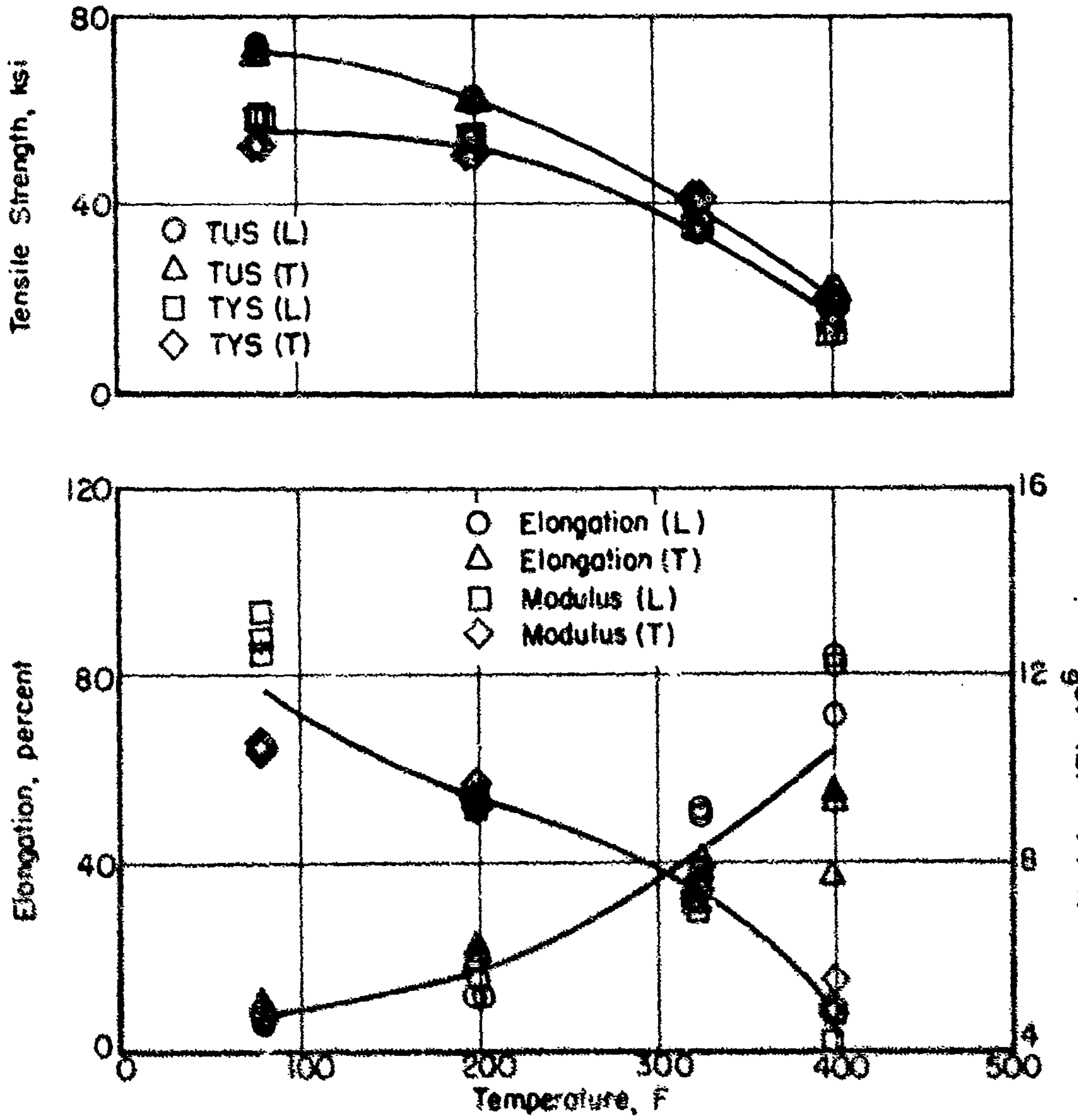


FIGURE 32. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF X5090 ALUMINUM SHEET

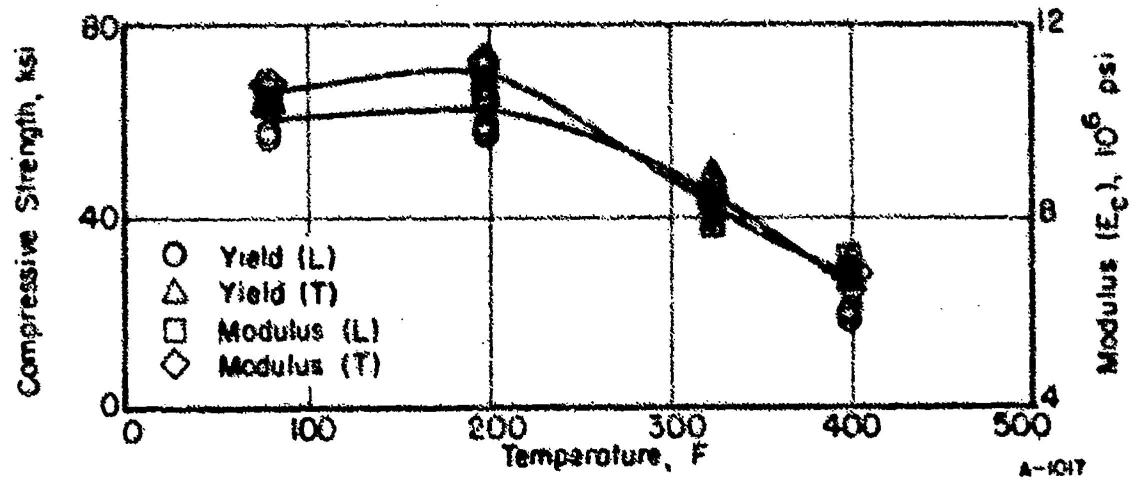


FIGURE 33. EFFECT OF TEMPERATURE ON THE COMPRESSIVE PROPERTIES OF X5090 ALUMINUM SHEET

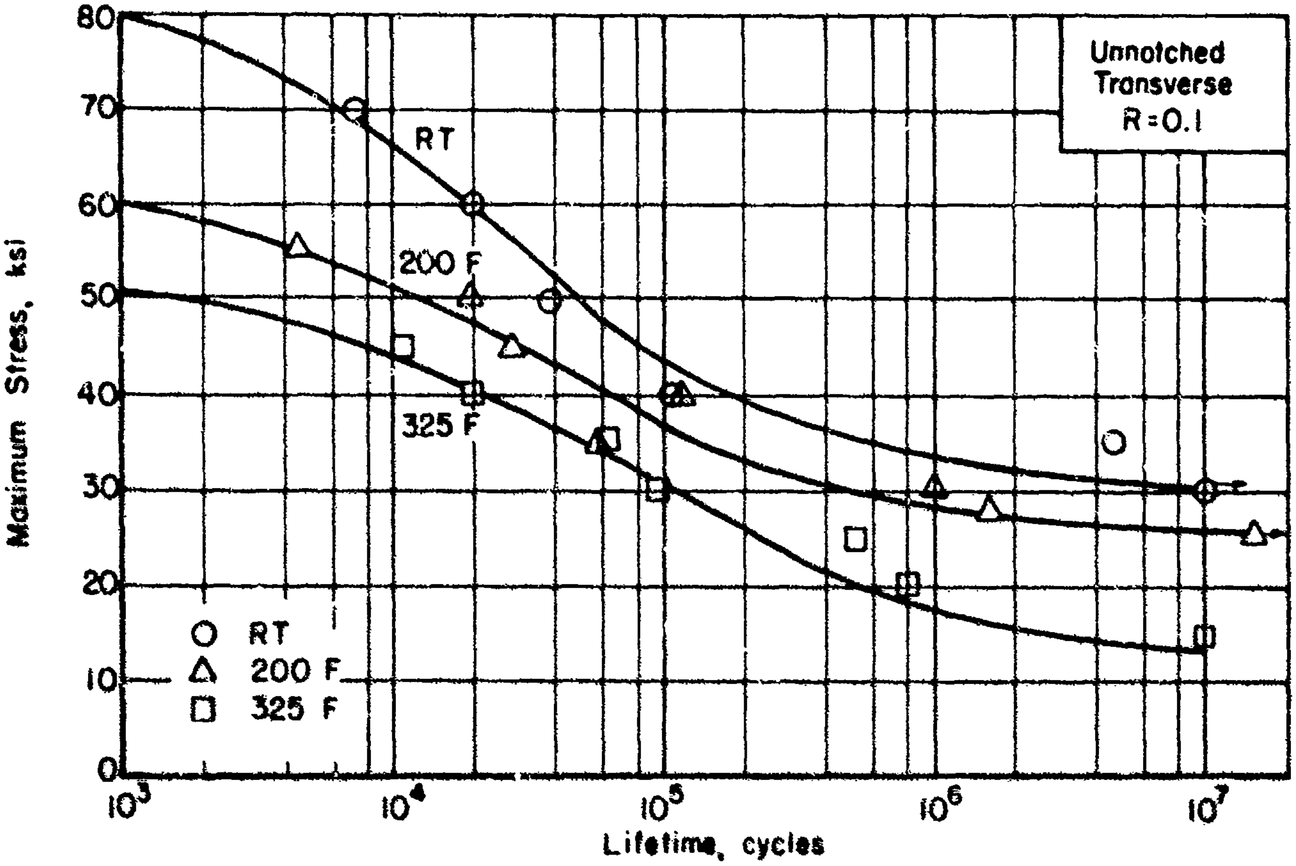


FIGURE 34. AXIAL-LOAD FATIGUE RESULTS FOR UNNOTCHED X5090 ALUMINUM SHEET

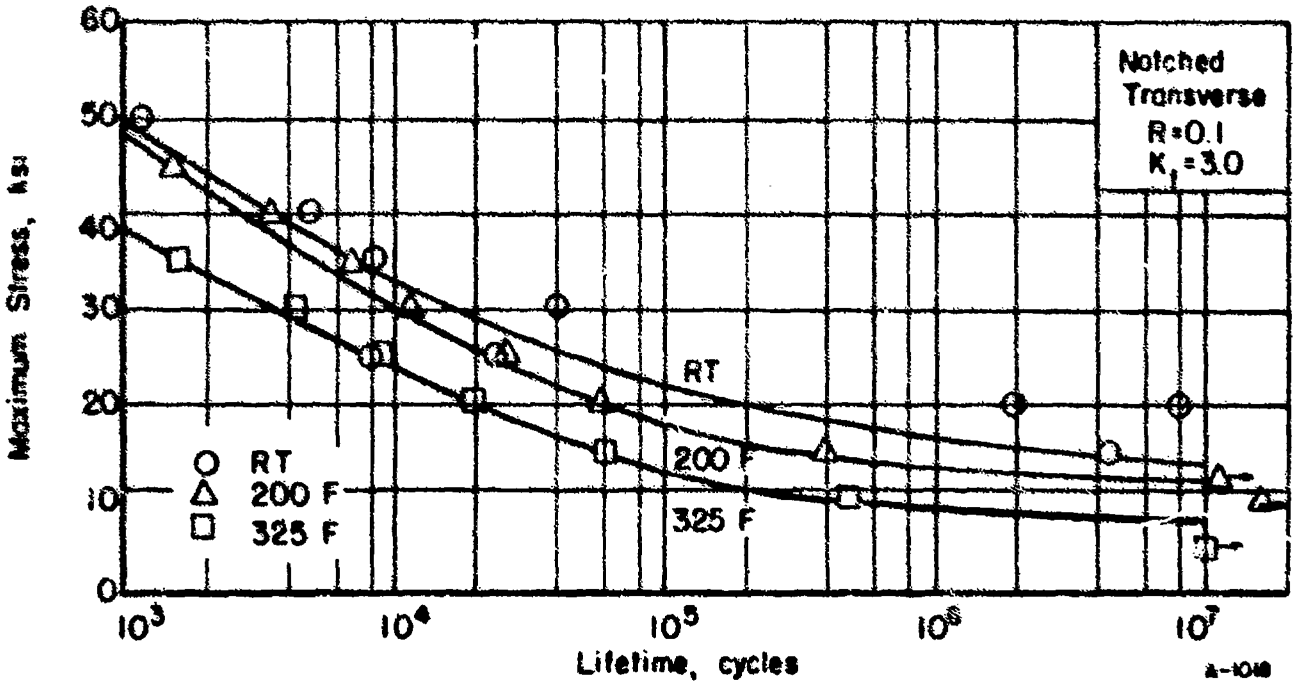


FIGURE 35. AXIAL-LOAD FATIGUE RESULTS FOR NOTCHED (K_t = 3.0) X5090 ALUMINUM SHEET

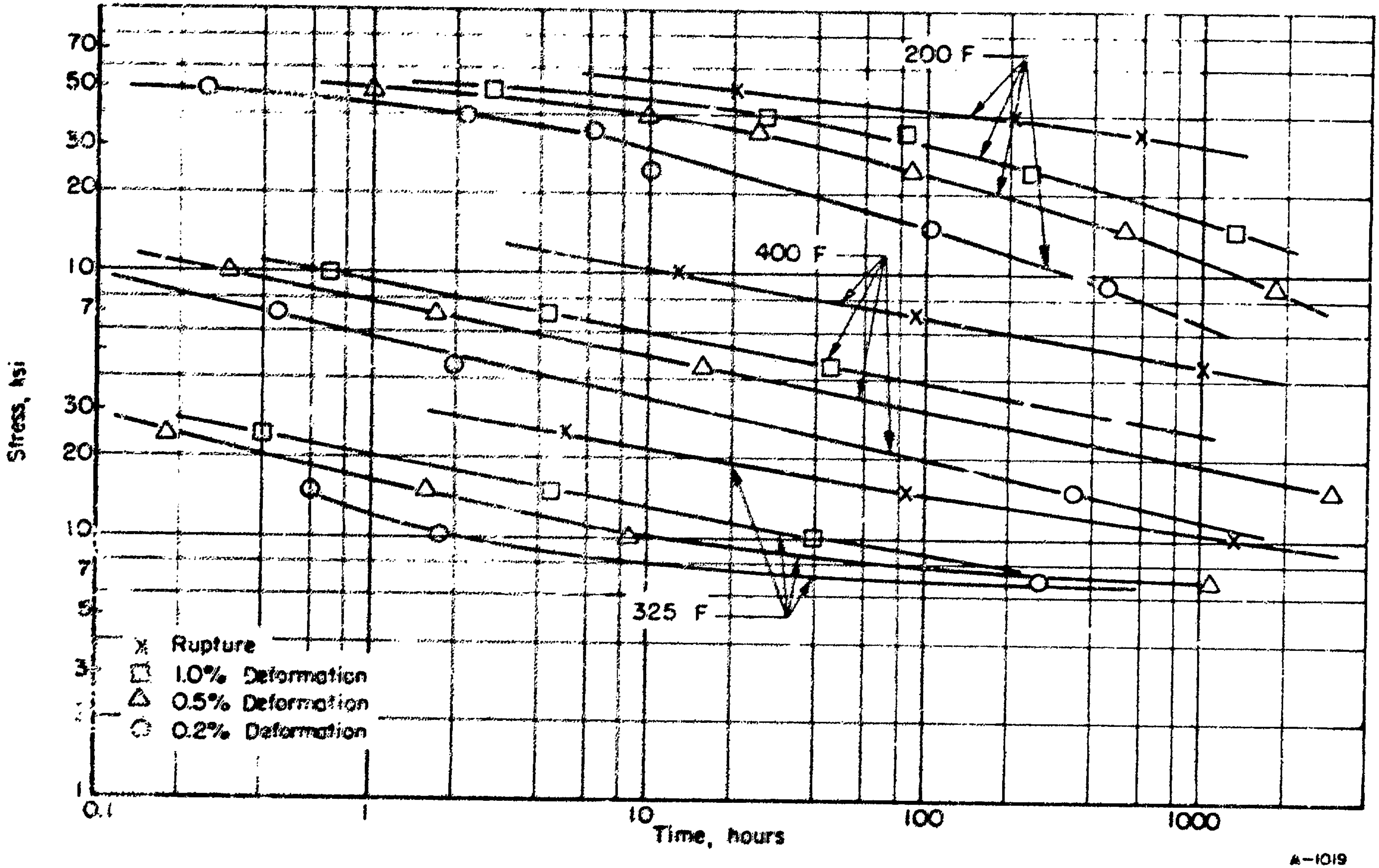


FIGURE 36. STRESS-RUPTURE AND PLASTIC DEFORMATION CURVES FOR X-5090 ALUMINUM SHEET

AF2-IDA Alloy

Material Description

AF2-IDA is a recently developed high-temperature nickel-base alloy. It was developed by the Universal-Cyclops Specialty Steel Division under Air Force Contract AF 33(616)-1729. Early development was in thick-section form for turbine wheel/bucket applications. An evaluation of extruded material is reported in Reference (3).

A sheet manufacturing process for AF2-IDA was developed at Union Carbide Corporation, also under Air Force Sponsorship (Contract F33615-3883). The 0.060-inch material evaluated and reported herein was supplied by the Air Force from the sheet manufacturing program.

The composition of the alloy was as follows:

Chemical Composition	Percent
Carbon	0.32
Molybdenum	2.98
Zirconium	0.10
Tantalum	1.60
Tungsten	5.79
Cobalt	9.68
Chromium	12.18
Aluminum	4.36
Titanium	3.16
Boron	0.014
Nickel	Balance

Processing and Heat Treating

The specimen layout for AF2-IDA is shown in Figure 37. The heat treatment used for the material was as follows:

2225 F for 2 hours with rapid air cool,

1950 F for 2 hours with air cool,

1400 F for 16 hours with air cool.

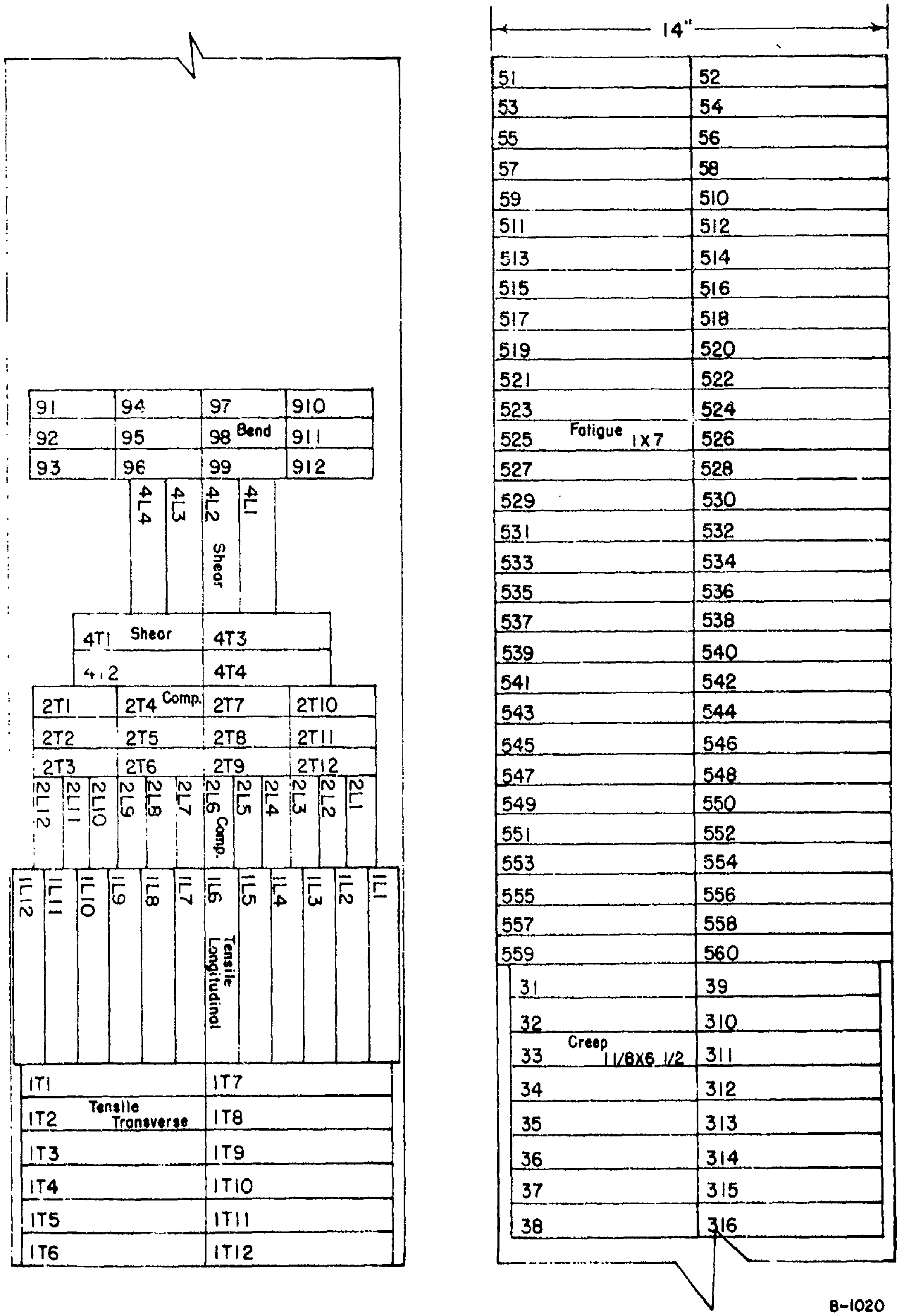


FIGURE 37. SPECIMEN LAYOUT FOR AF2-1DA SHEET

Test Results

Tension. Test results at room temperature, 1000 F, 1400 F, and 1800 F for both the longitudinal and transverse directions are given in tabular form in Table XIII. Stress-strain curves are presented in Figures 38 and 39. Effect-of-temperature curves are shown in Figure 42.

Compression. Results of tests in both the longitudinal and transverse directions at room temperature, 1000 F, 1400 F, and 1800 F are presented in Table XIV. Compressive stress-strain and tangent-modulus curves at temperature are shown in Figures 40 and 41. Effect-of-temperature curves are shown in Figure 43.

Shear. Results of room-temperature shear tests in the longitudinal and transverse directions are presented in Table XV.

Fracture Toughness. The material quantity was not sufficient for K_c tests.

Fatigue. Axial-load tests were conducted at room temperature, 1000 F, and 1400 F for both unnotched and notched transverse specimens. Tabular test results are presented in Tables XVI and XVII. S-N curves are shown in Figures 44 and 45.

Creep and Stress Rupture. Transverse tests were conducted at 1000 F, 1400 F, and 1800 F. Test results are given in tabular form in Table XVIII and presented as log stress-versus-log time curves in Figure 46.

Stress Corrosion. Tests were performed as described in the experimental procedure section of this report. No failures or cracks occurred in the 1000-hour test duration.

Thermal Expansion and Density. Values obtained are shown in the "data sheet" in the conclusions section of this report.

TABLE XIII. TENSION TEST RESULTS FOR AF2-1DA SHEET

Specimen No.	Ultimate Tensile Strength, ksi	0.2 Percent Offset Yield Strength, ksi	Elongation in 2 Inches, percent	Tensile Modulus, psi x 10^6
		Longitudinal at Room Temperature		
1L1	190.0	145.0	11.0[(a)]	31.2
1L2	191.0	143.0	12.5	31.8
1L3	194.0	145.0	12.5	32.8
		Transverse at Room Temperature		
1T1	177.0	143.0	10.5[(b)]	28.7
1T2	180.0	143.0	11.0	33.4
1T3	183.0	141.0	14.5	30.4
		Longitudinal at 1000 F		
1L4	151.0	136.0	2.0	26.9
1L5	154.0	137.0	2.5	28.5
1L6	154.0	139.0	2.5	28.8
		Transverse at 1000 F		
1T4	154.0	139.0	2.0	29.5
1T5	149.0	134.0	2.0	27.6
1T6	152.0	138.0	1.5	27.6
		Longitudinal at 1400 F		
1L7	126.0	--	0.5	25.4
1L8	132.0	131.0	1.0	23.4
1L9	132.0	129.0	1.0	24.1
		Transverse at 1400 F		
1T7	131.0	129.0	1.5	24.6
1T8	131.0	131.0	0.5[(c)]	23.4
1T9	132.0	130.0	1.0	--

TABLE XIII. (Concluded)

Specimen No.	Ultimate Tensile Strength, ksi	0.2 Percent Offset Yield Strength, ksi	Elongation in 2 Inches, percent	Tensile Modulus, psi x 10^6
		Longitudinal at 1800 F		
1L10	44.3	36.2	7.0[(d)]	17.9
1L11	45.9	37.2	8.5	--
1L12	48.9	38.9	8.0	18.5
		Transverse at 1800 F		
1T10	47.5	39.9	4.0[(c)]	--
1T11	48.4	40.6	5.5	19.7
1T12	48.6	40.1	6.5	17.7

(a) Failed in bench mark.

(b) Failed outside bench mark.

(c) Failed under knife edge.

(d) Grip pin sheared. Specimen width reduced to 0.250 inch and retested.

TABLE XIV. COMPRESSION TEST RESULTS FOR AF2-1DA SHEET

Specimen No.	0.2 Percent Offset Yield Strength, ksi	Compression Modulus, psi x 10^6
	Longitudinal at Room Temperature	
2L1	151.0	30.9
2L2	156.0	31.8
2L3	152.0	31.3
	Transverse at Room Temperature	
2T1	156.0	32.7
2T2	152.0	32.6
2T3	151.0	31.8
	Longitudinal at 1000 F	
2L4	145.0	36.8
2L5	143.0	34.9
2L6	141.0	31.1
	Transverse at 1000 F	
2T4	145.0	30.3
2T5	145.0	(a)
2T6	140.0	29.0
	Longitudinal at 1400 F	
2L7	134.0	26.2
2L8	136.0	25.3
2L9	139.0	(a)
	Transverse at 1400 F	
2T7	136.0	25.4
2T8	134.0	26.7
2T9	126.0	27.0

TABLE XIV. (Concluded)

Specimen No.	0.2 Percent Offset Yield Strength, ksi	Compression Modulus, psi x 10^6
	Longitudinal at 1800 F	
2L10	34.0	(a)
2L11	36.5	17.6
2L12	36.1	17.7
	Transverse at 1800 F	
2T10	37.8	(a)
2T11	39.1	18.4
2T12	39.7	18.0

(a) Curve not suitable for modulus.

TABLE XV. SHEAR TEST RESULTS FOR AF2-1DA SHEET

Specimen No.	Ultimate Shear Strength, ksi
	Longitudinal
4L-1	(a)
4L-2	(a)
4L-3	123.0
4L-4	118.0
	Transverse
4T-1	(a)
4T-2	122.0
4T-3	117.0
4T-4	121.0

(a) Did not fail in shear.

TABLE XVI. AXIAL-LOAD FATIGUE TEST RESULTS FOR UNNOTCHED AF2-1DA SHEET AT A STRESS RATIO OF R = 0.1

Specimen No.	Maximum Stress, ksi	Lifetime, cycles
	Room Temperature	
58	190	50
54	180	2,430
53	160	8,350
52	140	25,020
55	130	62,330
56	120	112,540
57	110	84,300
59	100	370,200
510	85	205,400
511	75	485,900
512	65	2,154,900
	1000 F	
517	160	5,050
516	140	7,900
515	120	62,860
514	100	344,220
519	80	310,750
521	80	4,478,720
	1400 F	
529	160	10
523	80	400
528	70	8,700
525	60	102,900
527	50	601,200
526	40	8,010,400

TABLE XVII. AXIAL-LOAD FATIGUE TEST RESULTS FOR NOTCHED (K_t = 3.0) AF2-1DA SHEET AT A STRESS RATIO OF R = 0.1

Specimen No.	Maximum Stress, ksi	Lifetime, cycles
532	140	2,420
531	110	6,290
542	80	22,500
543	60	72,960
533	40	1,068,600
534	35	1,077,400
535	25	11,610,900[a]
	1000 F	
545	100	1,460
550	80	4,880
544	70	11,580
549	60	18,550
546	50	19,370
548	40	8,373,670
	1400 F	
560	140	10
559	80	300
551	70	740
553	60	3,000
552	50	3,100
558	40	21,960
556	30	553,000
554	30	7,949,300
555	20	12,958,000[a]

(a) Did not fail.

TABLE XVIII. SUMMARY DATA ON CREEP AND RUPTURE PROPERTIES FOR AF2-IDA SHEET

Specimen No.	Stress, ksi	Temp, F	Hours to Indicated Creep Deformation, percent 0.1	0.2	0.5	1.0	2.0	Initial Strain, percent	Rupture Time, hr	Elongation in 2 Inches, percent	Minimum Creep Rate, percent/hr
AF2-5	160	1000	--	--	--	--	--	--	On loading	5.6	--
AF2-8	150	1000	0.3	1.0	--	--	--	3.092	1.7	3.7	0.15
AF2-11	145	1000	1.6	18.0	--	--	--	1.495	24.3	0.9	0.0047
AF2-10	140	1000	120.0	160.0[a]	--	--	--	0.623	164.0	0.9	0.00026
AF2-2	80	1400	2.5	6.5	20.0	--	--	0.241	25.2	0.9	0.022
AF2-3	70	1400	3.0	14.0	46.0	--	--	0.413	62.6	1.4	0.0095
AF2-6	50	1400	10.0	72.0	245.0	--	--	0.257	411.7	0.9	0.0017
AF2-9	35	1400	30.0	200.0	830.0[a]	--	--	0.199	335.9[b]	0.468	0.00048
AF2-13	25	1400	118.0	625.0	2800.0[a]	--	--	0.160	626.9[b]	0.361	0.00015
AF2-1	20	1800	0.08	0.2	0.7	1.8	3.5	0.298	6.8	7.9	0.51
AF2-4	10	1800	0.45	1.7	7.5	16.5	32.0	0.157	73.7	9.3	0.055
AF2-7	5	1800	12.0	33.0	85.0	160.0	275.0	0.016	736.8	13.4	0.0057
AF2-12	2.5	1800	440.0	900.0[a]	2900.0[a]	--	--	0	842.7[b]	0.171	0.00015

(a) Estimated.
(b) Test discontinued.

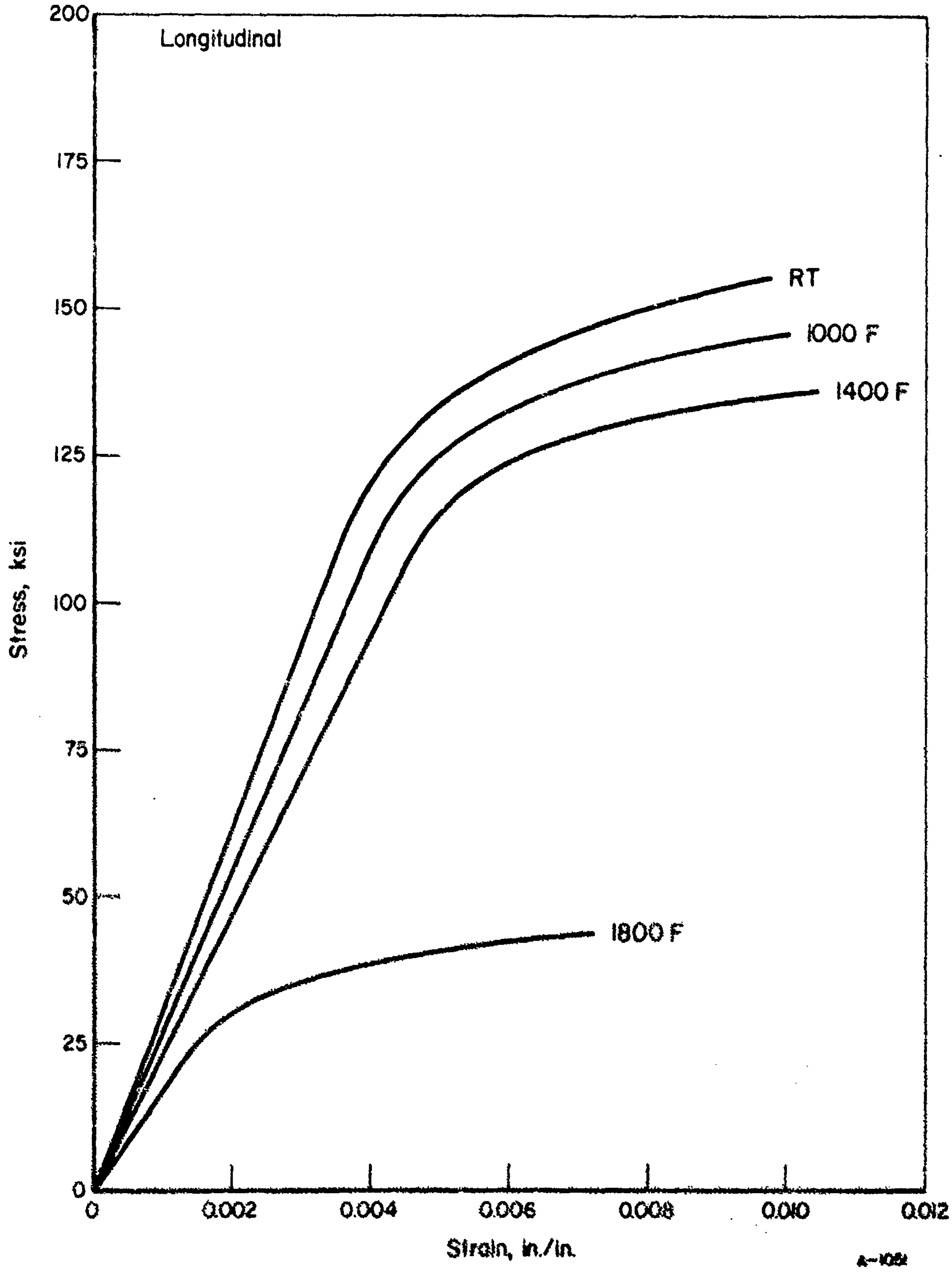


FIGURE 38. TYPICAL TENSILE STRESS-STRAIN CURVES FOR AF2-IDA SHEET (LONGITUDINAL)

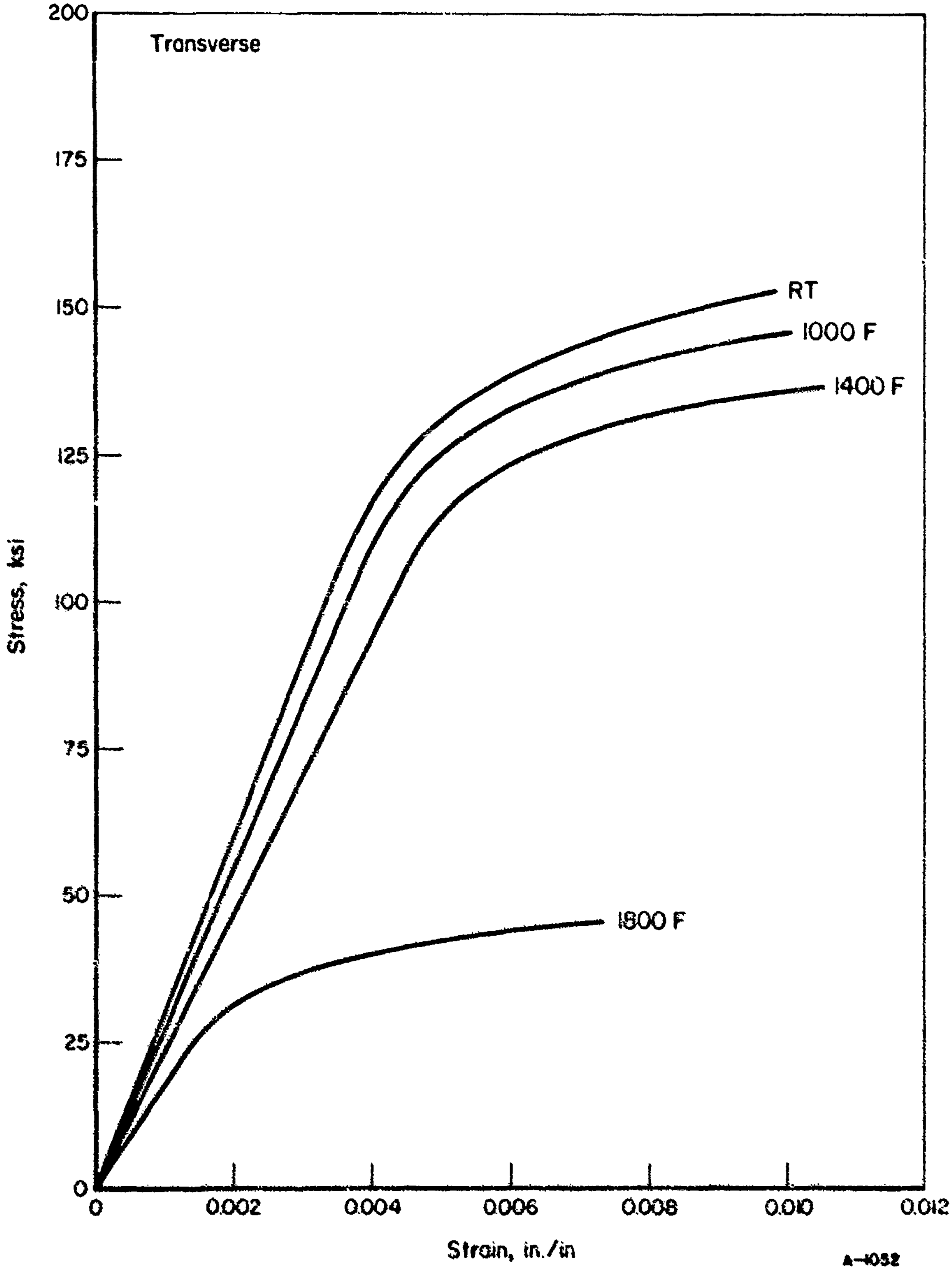


FIGURE 39. TYPICAL TENSILE STRESS-STRAIN CURVES FOR AF2-IDA SHEET (TRANSVERSE)

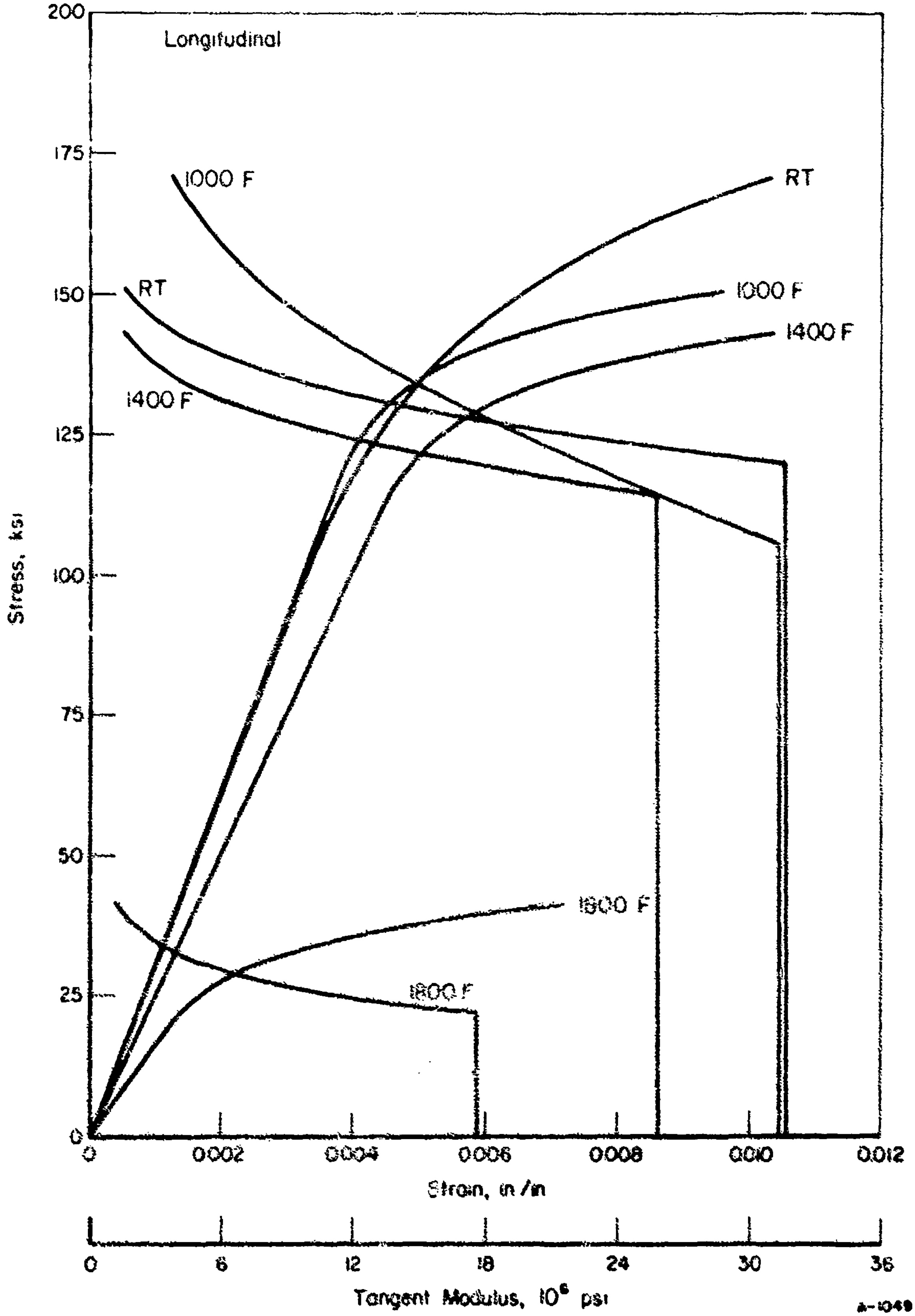


FIGURE 40. TYPICAL COMPRESSION STRESS-STRAIN AND TANGENT MODULUS CURVES FOR AF2-IDA SHEET (LONGITUDINAL)

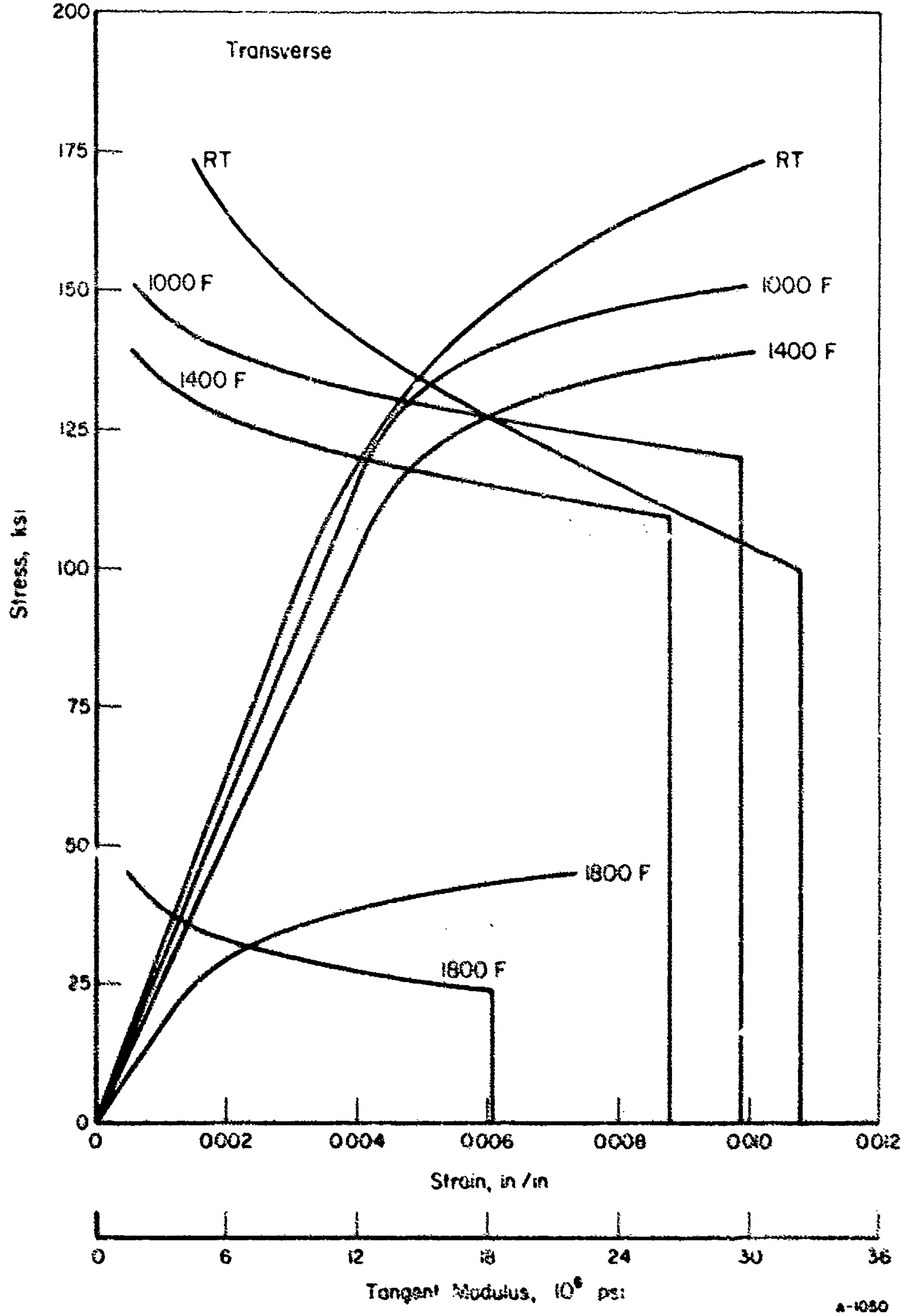


FIGURE 41. TYPICAL COMPRESSION STRESS-STRAIN AND TANGENT MODULUS CURVES FOR AF2-1DA SHEET (TRANSVERSE)

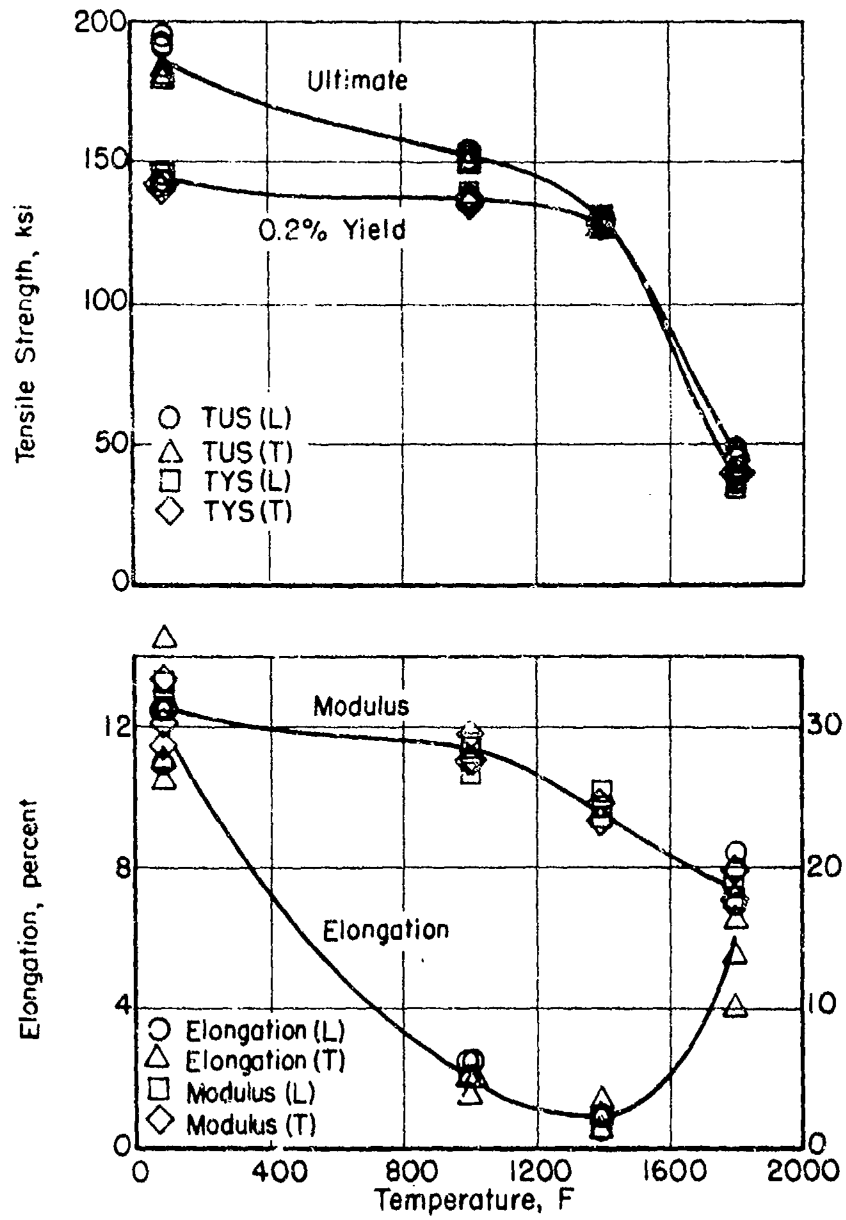


FIGURE 42. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF AF2-1DA SHEET

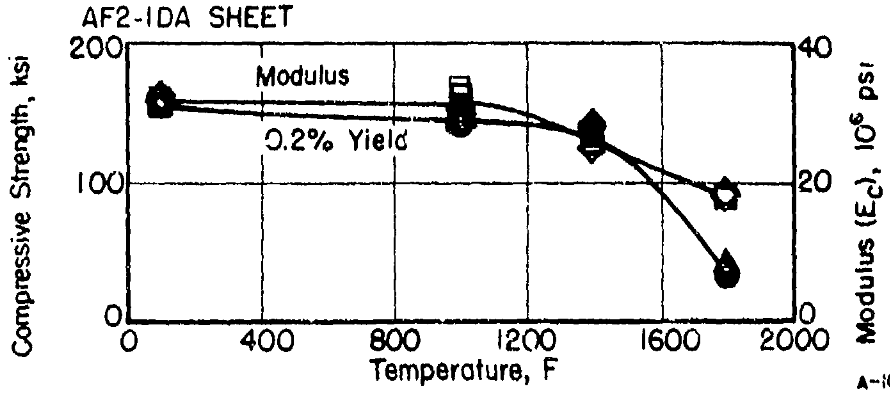


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FIGURE 43. EFFECT OF TEMPERATURE ON THE COMPRESSIVE PROPERTIES OF AF2-1DA SHEET

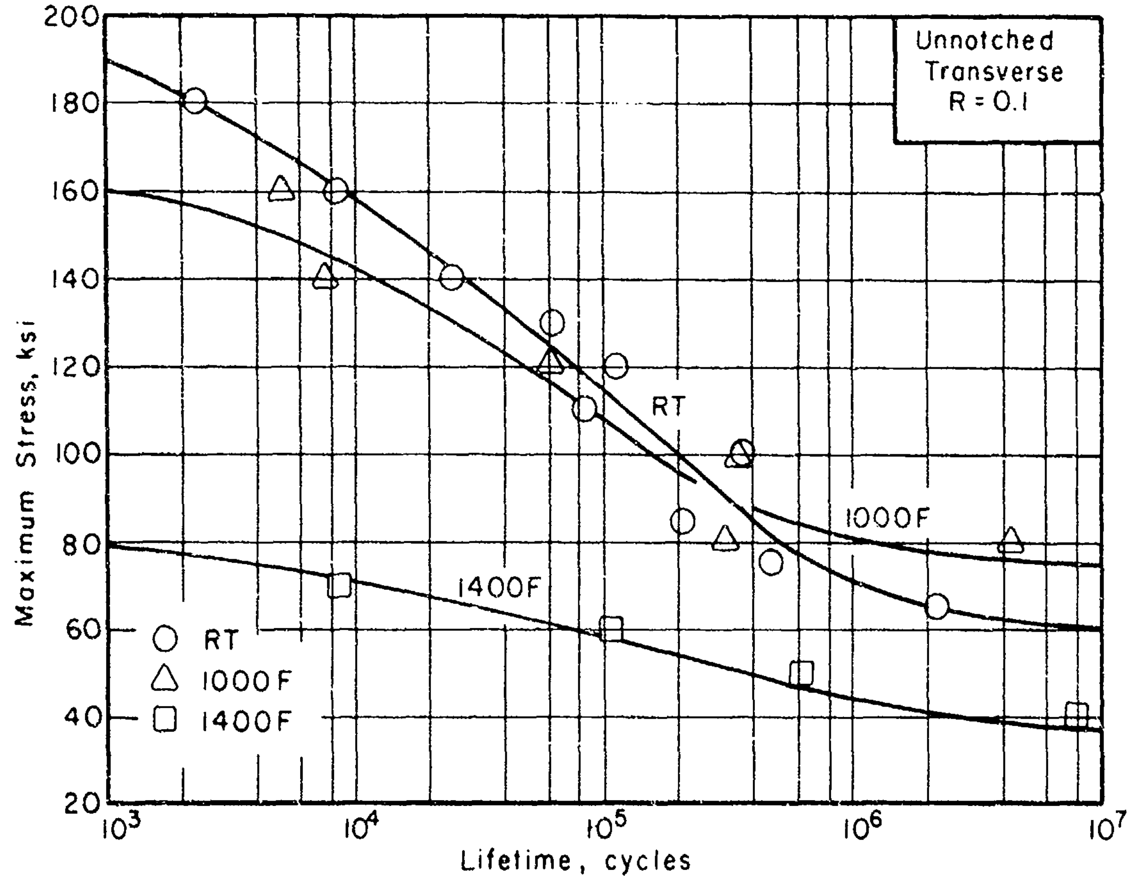

FIGURE 44. AXIAL-LOAD FATIGUE RESULTS FOR UNNOTCHED AF2-1DA SHEET

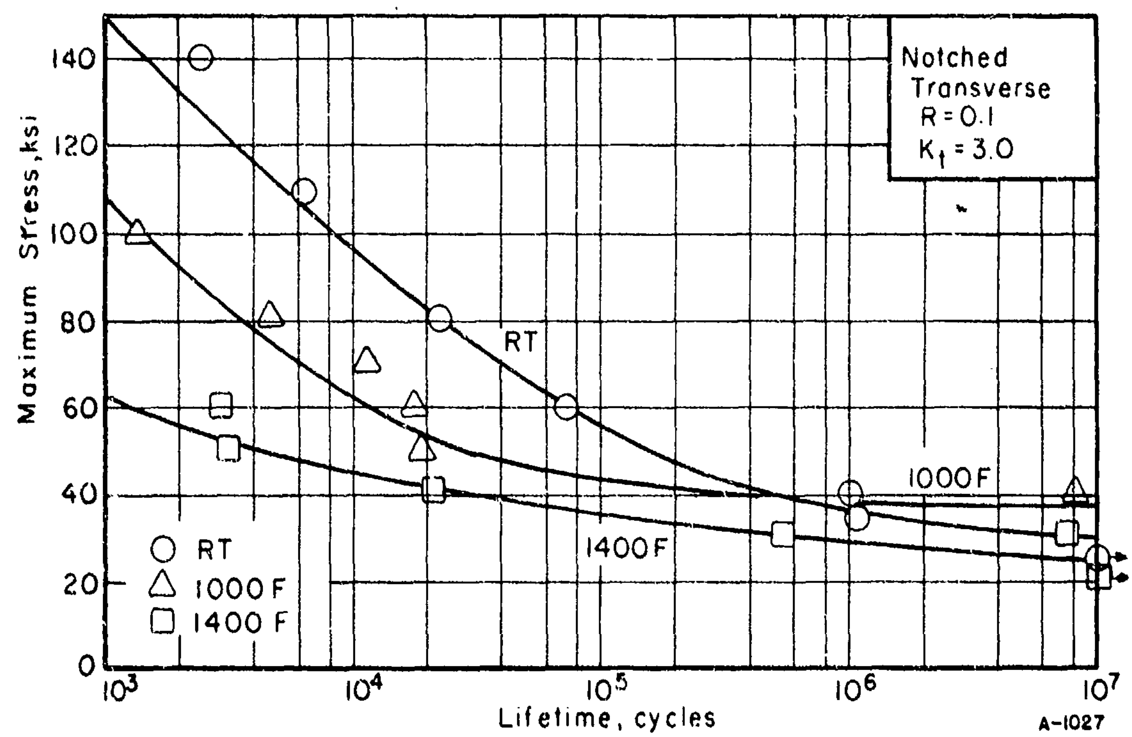

FIGURE 45. AXIAL-LOAD FATIGUE RESULTS FOR NOTCHED (K_t = 3.0) AF2-1DA SHEET

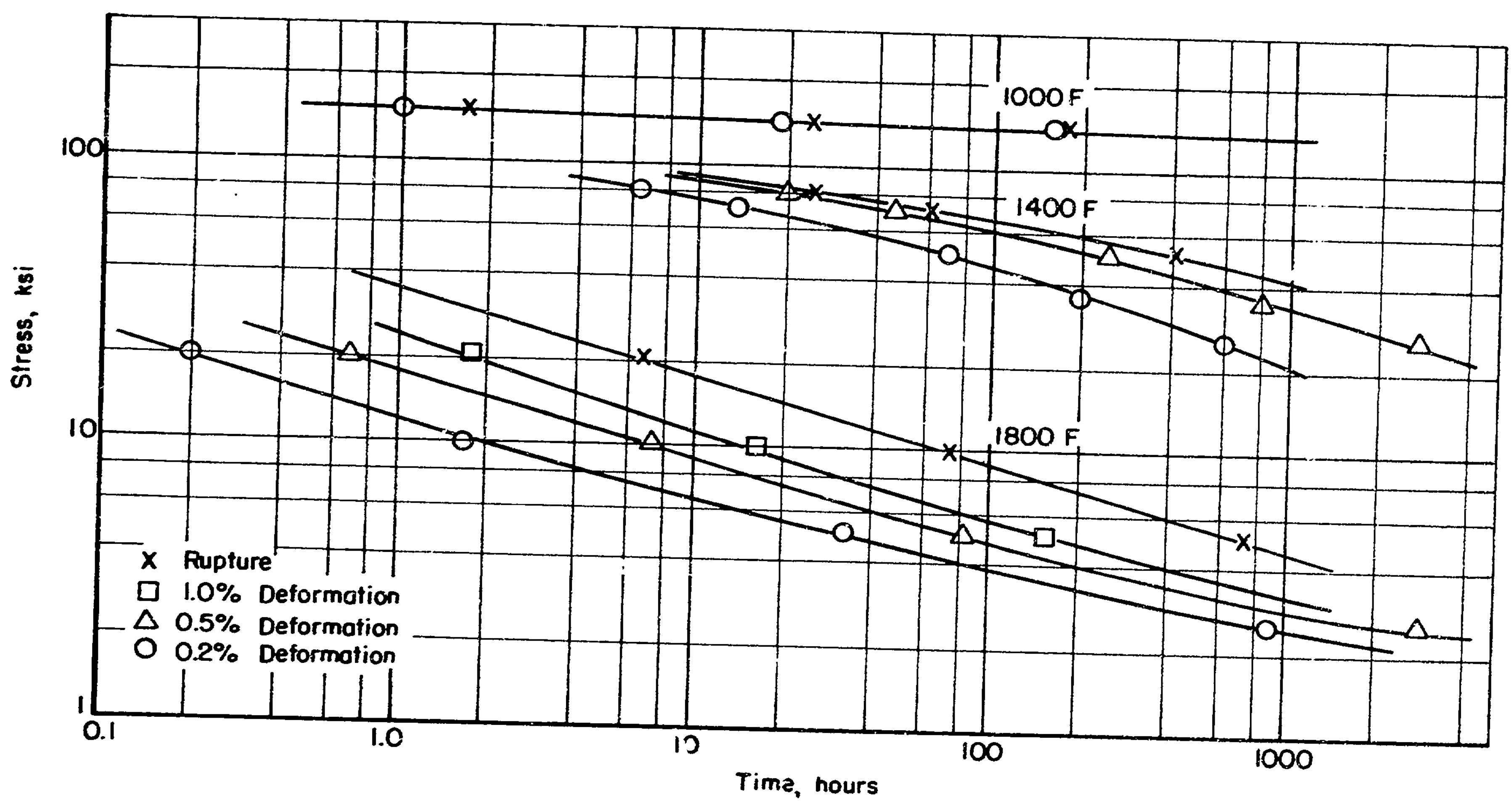

FIGURE 46. STRESS-RUPTURE AND PLASTIC DEFORMATION CURVES FOR AF2-IDA SHEET

Inconel 625 Alloy

Material Description

Inconel 625 is a relatively new product of Huntington Alloy Products Division of The International Nickel Company. It is reported to have high strength and toughness from cryogenic temperatures to 2000 F. Inconel 625 is a nonmagnetic alloy deriving its strength from the stiffening effect of molybdenum and columbium on its nickel-chromium matrix. It has good oxidation resistance and is virtually immune to chloride-ion stress-corrosion cracking.

The alloy is readily fabricated by common industrial practices and has excellent weld qualities, requiring no postweld thermal treatment for maintenance of its corrosion resistance. The material has been used in numerous aerospace applications and is currently being evaluated for use in the chemical and marine fields.

The composition of the material evaluated on this program is as follows:

Chemical Composition	Percent
Carbon	0.04
Manganese	0.04
Iron	3.30
Sulfur	0.006
Silicon	0.20
Chromium	22.12
Aluminum	0.27
Titanium	0.25
Molybdenum	9.13
Columbium + Tantalum	3.47
Nickel	Balance

The material was obtained as 0.125-inch x 36-inch x 120-inch sheet.

Processing and Heat Treating

The specimen layout for Inconel 625 sheet is shown in Figure 47. The alloy was tested in the as-received annealed condition.

Test Results

Tension. Results of tests in both the longitudinal and transverse directions at room temperature, 800 F, 1200 F, and 1600 F are presented in Table XIX. Stress-strain curves at temperature are shown in Figures 48 and 49. Effect-of-temperature curves are presented in Figure 52.

Compression. Results of tests in both the longitudinal and transverse directions at room temperature, 800 F, 1200 F, and 1600 F are given in tabular form in Table XX. Compressive stress-strain and tangent-modulus curves at temperature are shown in Figures 50 and 51. Effect-of-temperature curves are shown in Figure 53.

Shear. Results of room temperature tests in both the longitudinal and transverse directions are presented in Table XXI.

Bend. Test results are given in the "data sheet" in the conclusions section of this report.

Fracture Toughness. Tests were conducted on specimens of full sheet thickness x 18 inches x 48 inches. Average K_c was 158 ksi$\sqrt{\text{in.}}$ The net section yield stress at fracture was greater than the tensile yield strength of the material. Therefore, the K_c values are considered not valid.

Fatigue. Axial-load test results at room temperature, 800 F, and 1200 F for unnotched and notched transverse specimens are presented in tabular form in Tables XXII and XXIII. S-N curves are shown in Figures 54 and 55.

Creep and Stress-Rupture. Tests were conducted at 800 F, 1200 F, and 1600 F on transverse specimens. Results are presented in tabular form in Table XXIV. Log stress-versus-log time curves are shown in Figure 56.

Stress Corrosion. Tests were conducted as described in the experimental procedure section of this report. No failures or cracks occurred in the 1000-hour test duration.

Thermal Expansion and Density. Values obtained are presented in the "data sheet" in the conclusions section of this report.

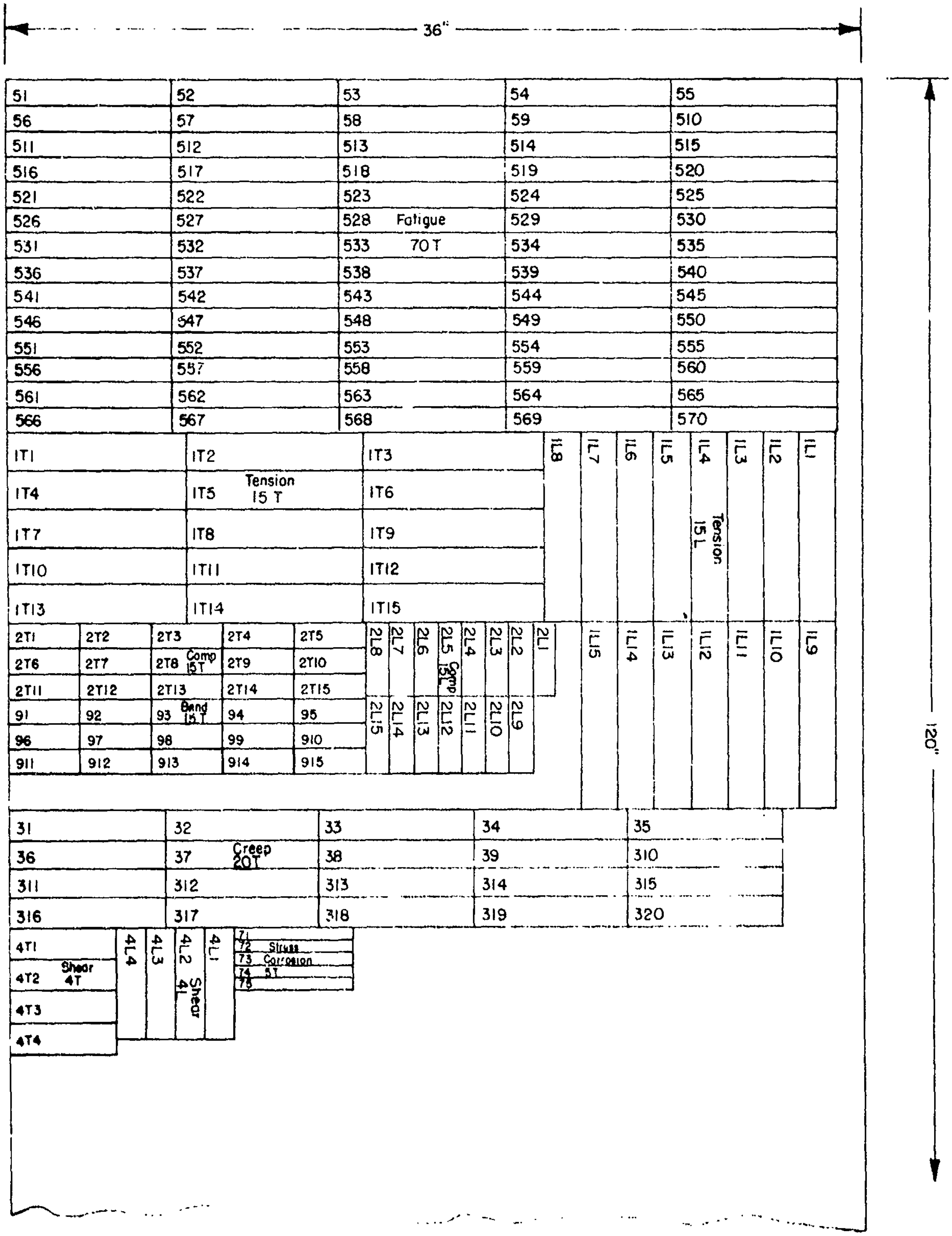

FIGURE 47. SPECIMEN LAYOUT FOR INCONEL 625 SHEET

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TABLE XIX. TENSION TEST RESULTS FOR INCONEL 625 SHEET

Specimen No.	Ultimate Tensile Strength, ksi	0.2 Percent Offset Yield Strength, ksi	Elongation in 2 Inches, percent	Tensile Modulus, psi x 10^6
		Longitudinal at Room Temperature		
1L1	139.0	69.9	52.0	28.4
1L2	139.0	69.2	51.0	28.4
1L3	138.0	69.4	51.0	28.1
		Transverse at Room Temperature		
1T1	137.0	69.5	50.0	30.7
1T2	137.0	70.0	51.0	30.2
1T3	136.0	69.8	49.0	30.1
		Longitudinal at 800 F		
1L4	124.0	52.9	51.0	24.1
1L5	123.0	53.7	50.0	23.6
1L6	123.0	53.2	50.0	24.5
		Transverse at 800 F		
1T4	122.0	53.8	51.0	25.7
1T5	122.0	54.3	48.0	24.1
1T6	123.0	53.7	53.0	25.1
		Longitudinal at 1200 F		
1L7	113.0	49.4	96.0	22.0
1L8	111.0	48.4	110.0	22.9
1L9	113.0	48.9	84.0	22.7
		Transverse at 1200 F		
1T7	114.0	49.8	75.0	23.5
1T8	112.0	49.1	91.0	25.4
1T9	113.0	50.0	78.0	25.3

TABLE XIX. (Concluded)

Specimen No.	Ultimate Tensile Strength, ksi	0.2 Percent Offset Yield Strength, ksi	Elongation in 2 Inches, percent	Tensile Modulus, psi x 10^6
		Longitudinal at 1600 F		
1L10	28.3	28.2	127.0	15.4
1L11	30.1	29.9	113.0	14.1
1L12	31.0	31.0	129.0	(a)
		Transverse at 1600 F		
1T10	29.0	29.0	121.0	17.8
1T11	30.4	30.1	110.0	17.5
1T12	28.5	28.4	124.0	18.9

(a) Load-strain curve not suitable for modulus determination.

TABLE XX. COMPRESSION TEST RESULTS FOR INCONEL 625 SHEET

Specimen No.	0.2 Percent Offset Yield Strength, ksi	Compression Modulus, psi x 10^6
	Longitudinal at Room Temperature	
2L1	71.6	29.4
2L2	71.4	28.8
2L3	71.4	29.0
	Transverse at Room Temperature	
2T1	73.0	30.2
2T2	73.4	31.1
2T3	73.8	30.8
	Longitudinal at 800 F	
2L4	57.1	23.2
2L5	57.6	23.8
2L6	57.9	25.1
	Transverse at 800 F	
2T4	59.5	26.1
2T5	58.4	26.3
2T6	59.2	(a)
	Longitudinal at 1200 F	
2L7	54.1	25.4
2L8	57.8	23.9
2L9	55.0	25.1
	Transverse at 1200 F	
2T7	54.7	24.7
2T8	55.1	25.7
2T9	54.9	25.2

TABLE XX. (Concluded)

Specimen No.	0.2 Percent Offset Yield Strength, ksi	Compression Modulus, psi x 10^6
	Longitudinal at 1600 F	
2L10	31.9	15.4
2L11	31.2	15.5
2L12	31.6	15.5
	Transverse at 1600 F	
2T10	32.0	14.0
2T11	30.8	14.4
2T12	31.0	14.3

(a) Load-strain curve not suitable for modulus determination.

TABLE XXI. SHEAR TEST RESULTS FOR INCONEL 625 SHEET AT ROOM TEMPERATURE

Specimen No.	Ultimate Shear Strength, ksi
	Longitudinal
4L-1	116.0
4L-2	112.0
4L-3	112.0
4L-4	118.0
	Transverse
4T-1	115.0
4T-2	115.0
4T-3	119.5
4T-4	113.5

TABLE XXII. AXIAL-LOAD FATIGUE TEST RESULTS FOR UNNOTCHED INCONEL 625 SHEET AT A STRESS RATIO OF R = 0.1

Specimen No.	Maximum Stress, ksi	Lifetime, cycles
	Room Temperature	
513	140	13
517	130	23,970
512	120	49,754
516	110	72,400
511	100	117,730
515	90	262,200
510	80	8,583,300
514	70	11,224,100[(a)]
	800 F	
529	120	160
533	115	26,900
534	110	30,210
527	110	34,550
528	105	56,030
535	100	10,483,900[(a)]
	1200 F	
51	100	300
53	95	5,090
56	90	9,760
52	85	33,180
59	80	43,700
537	75	14,244,400[(a)]
54	70	12,054,580[(a)]
58	60	10,182,900[(a)]

(a) Did not fail.

TABLE XXIII. AXIAL-LOAD FATIGUE TEST RESULTS FOR NOTCHED (K_t = 3.0) INCONEL 625 SHEET AT A STRESS RATIO OF R = 0.1

Specimen No.	Maximum Stress, ksi	Lifetime, cycles
	Room Temperature	
543	120	2,386
542	110	3,840
536	100	5,180
537	80	13,810
544	70	63,298
538	60	119,800
539	50	5,964,200
540	50	443,700
541	40	10,032,400[(a)]
	800 F	
547	100	2,333
546	90	3,300
545	80	15,820
549	70	11,600
568	60	43,020
567	50	84,070
566	40	13,655,200[(a)]
	1200 F	
550	80	406
555	70	4,200
556	65	5,300
551	60	10,200
554	55	1,614,000
553	50	3,110,200
552	40	10,141,300[(a)]

(a) Did not fail.

TABLE XXIV. SUMMARY DATA ON CREEP AND RUPTURE PROPERTIES FOR INCONEL 625 SHEET

Specimen No.	Stress, ksi	Temp. F	Hours to Indicated Creep Deformation, percent 0.1	0.[illegible]	0.5	1.0	2.0	Initial Strain, percent	Rupture Time, hr	Elongation in 2 Inches, percent	Minimum Creep Rate, percent/hr
3[illegible]	127.7	800	(Extensometer inoperable due to large initial strain)					-40.0	On loading(b)	40.4	--
38	120.0	800						-40.0	431.1(b)	41.7	--
35	90.0	800	Negative creep occurred					9.438	531.0(b)	0.420	--
36	50.0	800	ditto					0.217	379.7(b)	0.167	--
311	90.0	1200	0.03	0.[illegible]	0.23	0.5	[illegible].0	7.137	10.0	49.3	1.8
310	80.0	1200	0.2	0.6	2.[illegible]	5.7	11.0	2.321	54.5	23.6	0.16
37	70.0	1200	0.6	1.8	7.0	25.0	77.0	1.322	163.2	18.2	0.017
34	62.0	1200	80.0	123.0	203.0	275.0	340.0	0.233	686.7	15.1	0.0015
312	57.0	1200	[illegible]5.0	130.0	325.0	480.0	--	0.378	337.7(b)	0.935	0.0005
314	52.0	1200	200.0	365.0	63.5	500.0(b)	--	0.240	717.2(b)	0.840	0.00036
31	10.0	1600	0.43	0.70	[illegible].3	2.[illegible]	4.0	0.035	28.3	35.1	0.38
32	6.0	1600	0.70	1.3	4.0	8.[illegible]	18.8	0.042	166.9	37.0	0.10
33	3.5	1600	[illegible]	6.0	18.0	40.0	107.0	0.007	1035.0	80.0	0.014
39	2.0	1600	[illegible]6.0	[illegible]	[illegible]85.0	700.0(a)	1360.0(a)	0.013	360.0(b)	0.787	0.0015
313	[illegible].3	1600	[illegible]	50.0	425.0	1650.0(a)	--	0	480.6(b)	0.533	0.00040

(a) Estimated.
(b) Test discontinued.

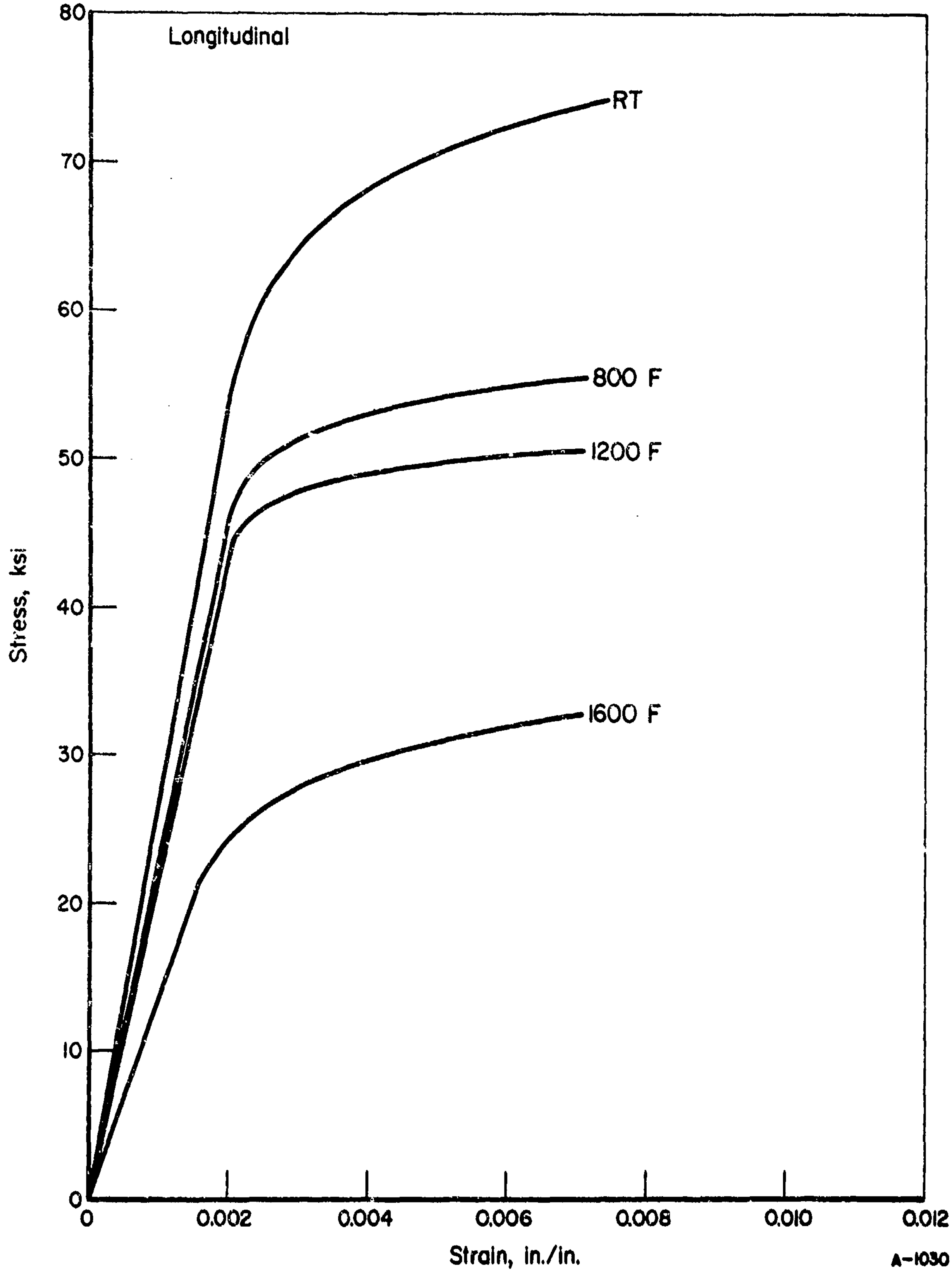

FIGURE 48. TYPICAL TENSILE STRESS-STRAIN CURVES FOR INCONEL 625 SHEET (LONGITUDINAL)

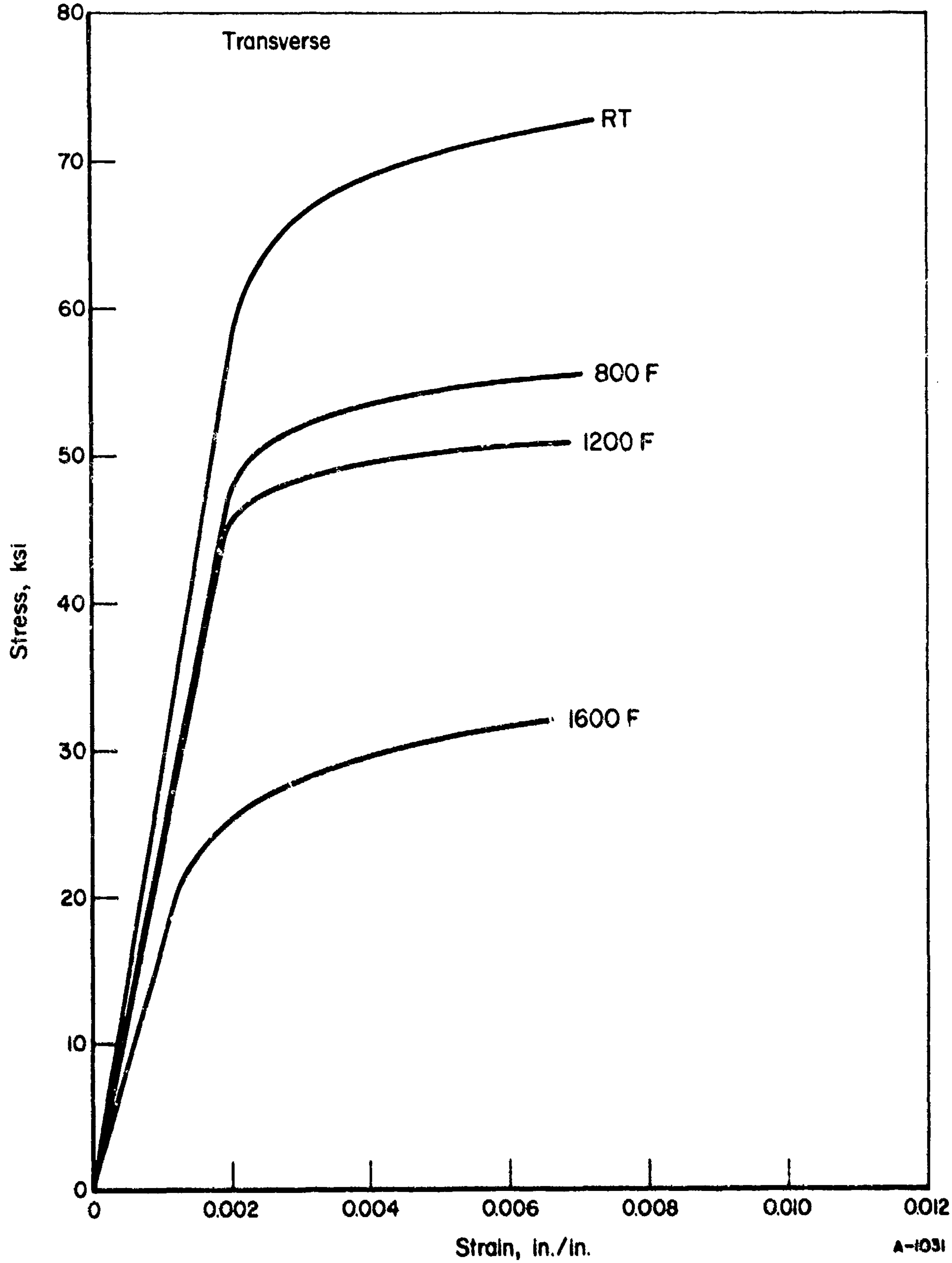

FIGURE 49. TYPICAL TENSILE STRESS-STRAIN CURVES FOR INCONEL 625 SHEET (TRANSVERSE)

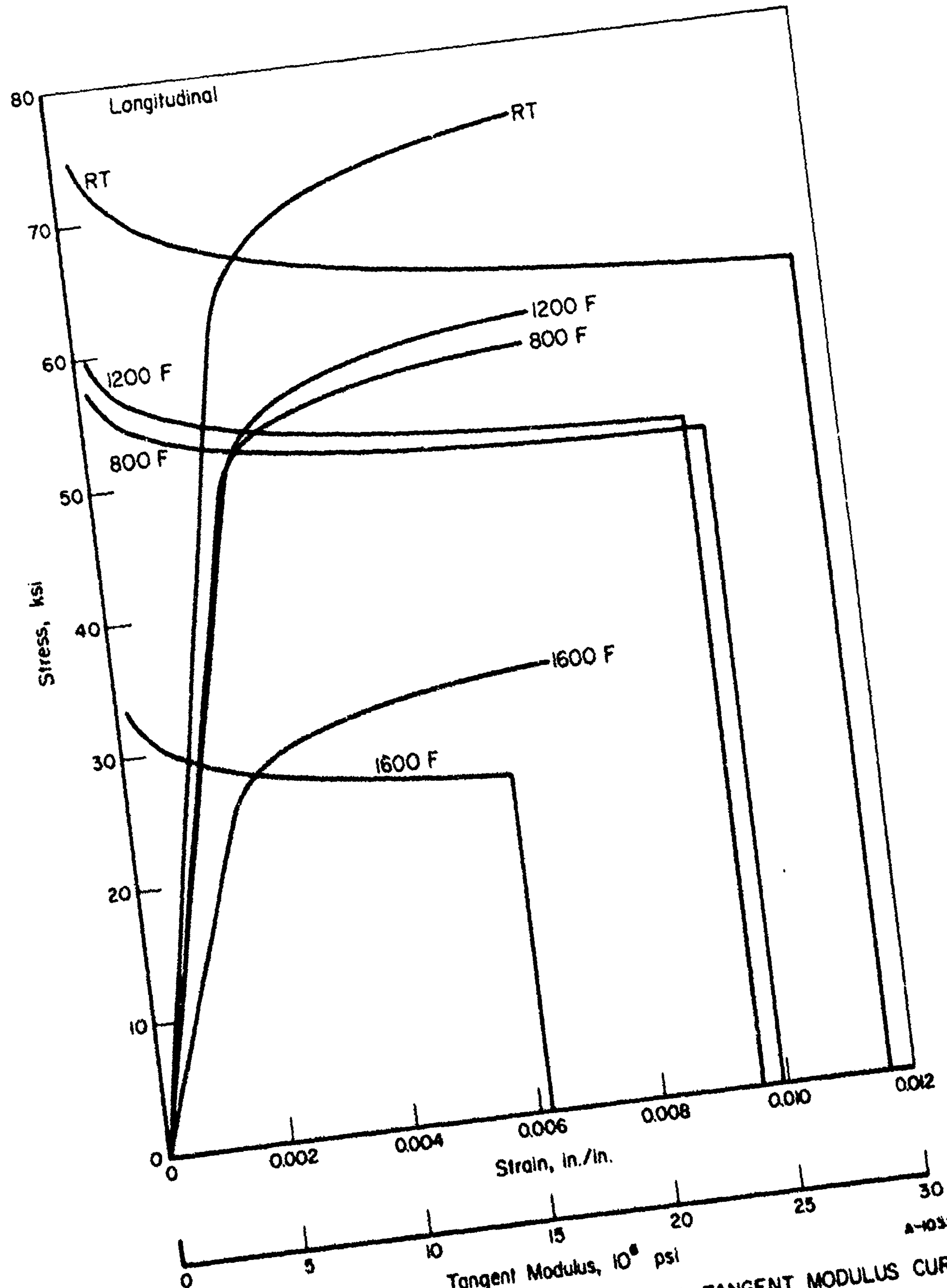

FIGURE 50. TYPICAL COMPRESSION STRESS-STRAIN AND TANGENT MODULUS CURVES FOR INCONEL 625 SHEET (LONGITUDINAL)

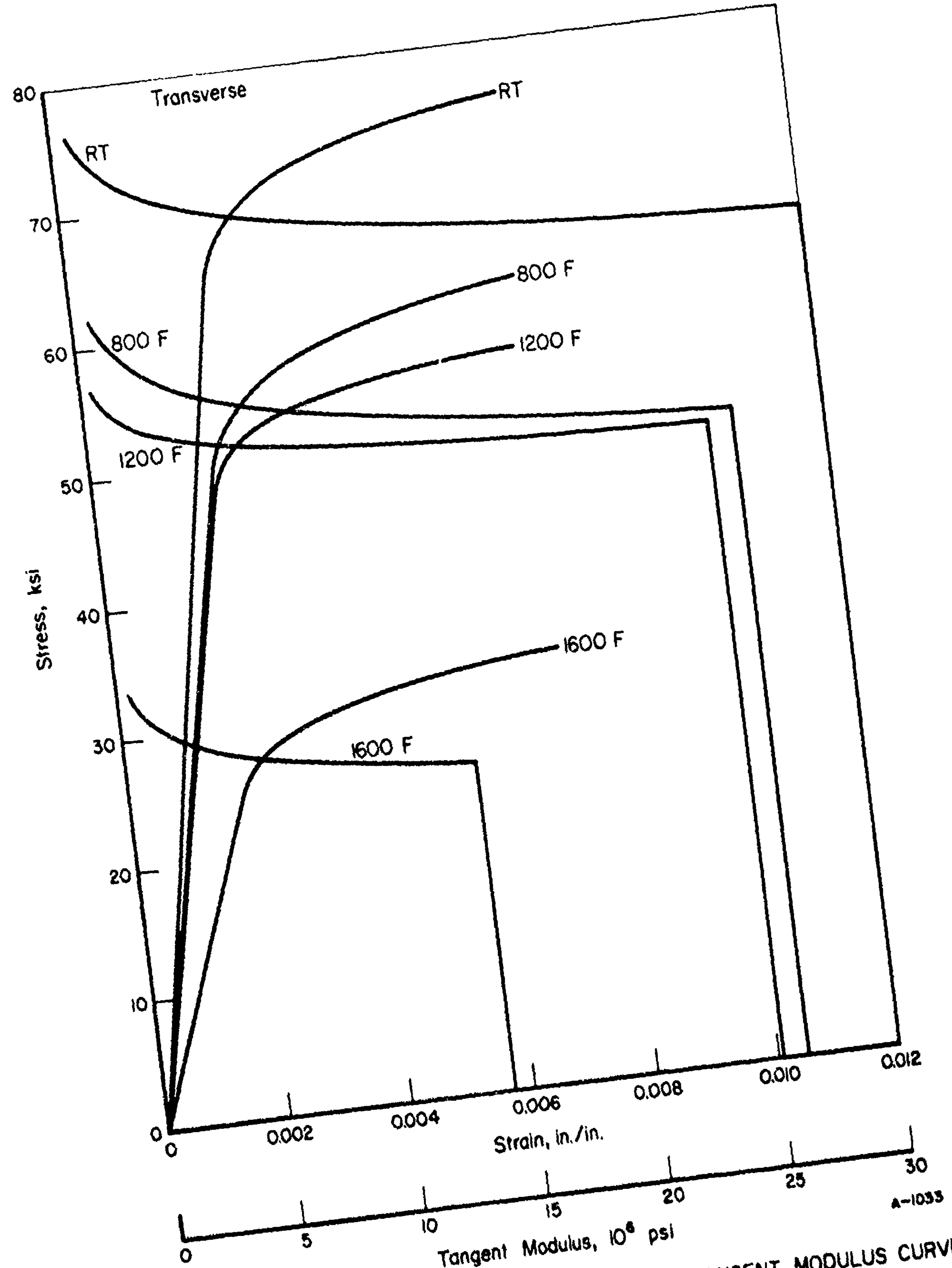

FIGURE 51. TYPICAL COMPRESSION STRESS-STRAIN AND TANGENT MODULUS CURVES FOR INCONEL 625 SHEET (TRANSVERSE)

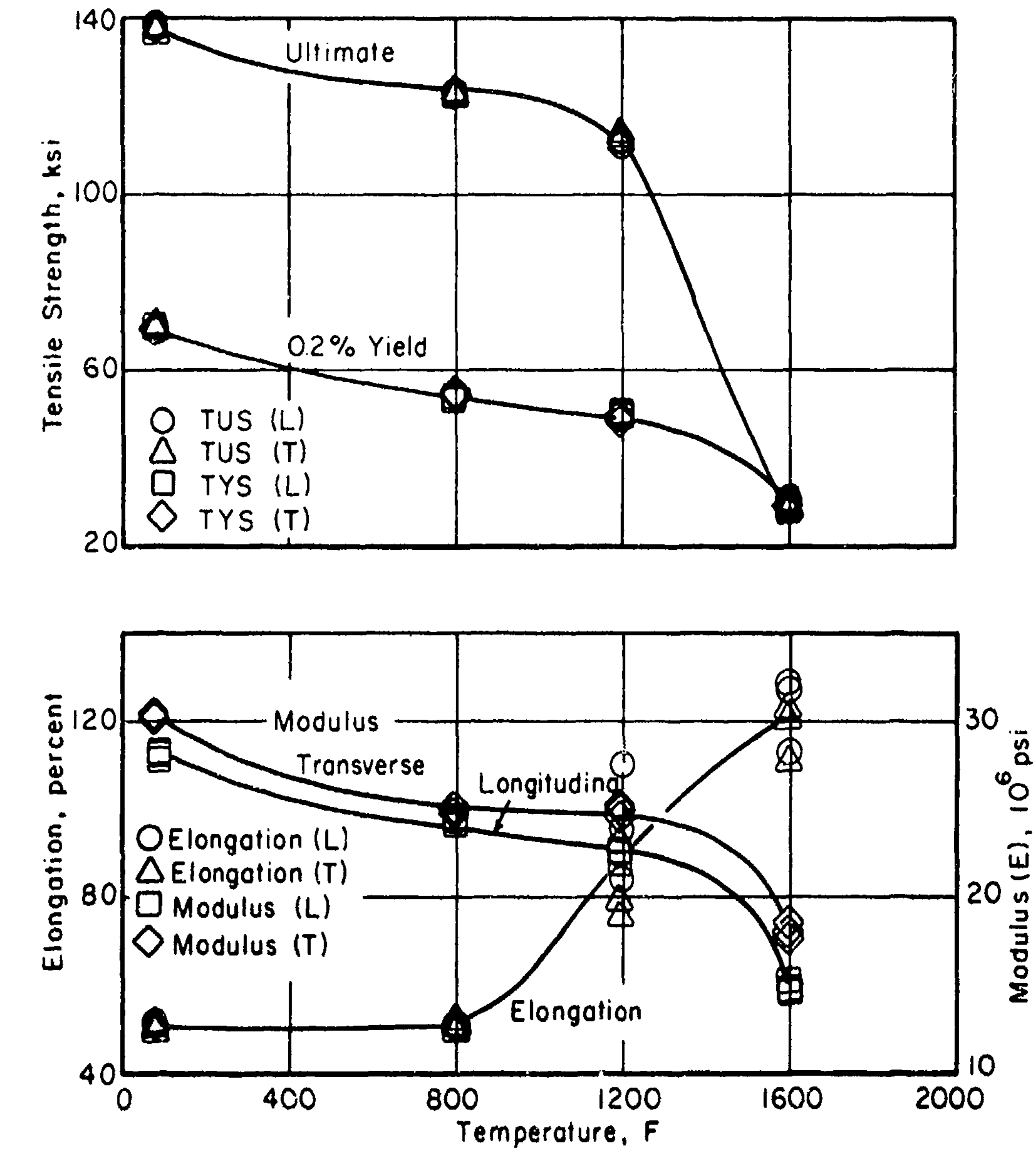

FIGURE 52. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF INCONEL 625 SHEET

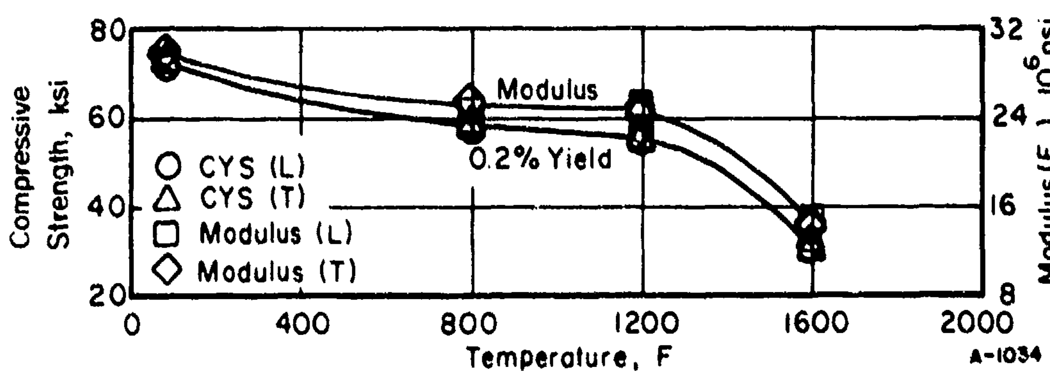

FIGURE 53. EFFECT OF TEMPERATURE ON THE COMPRESSIVE PROPERTIES OF INCONEL 625 SHEET

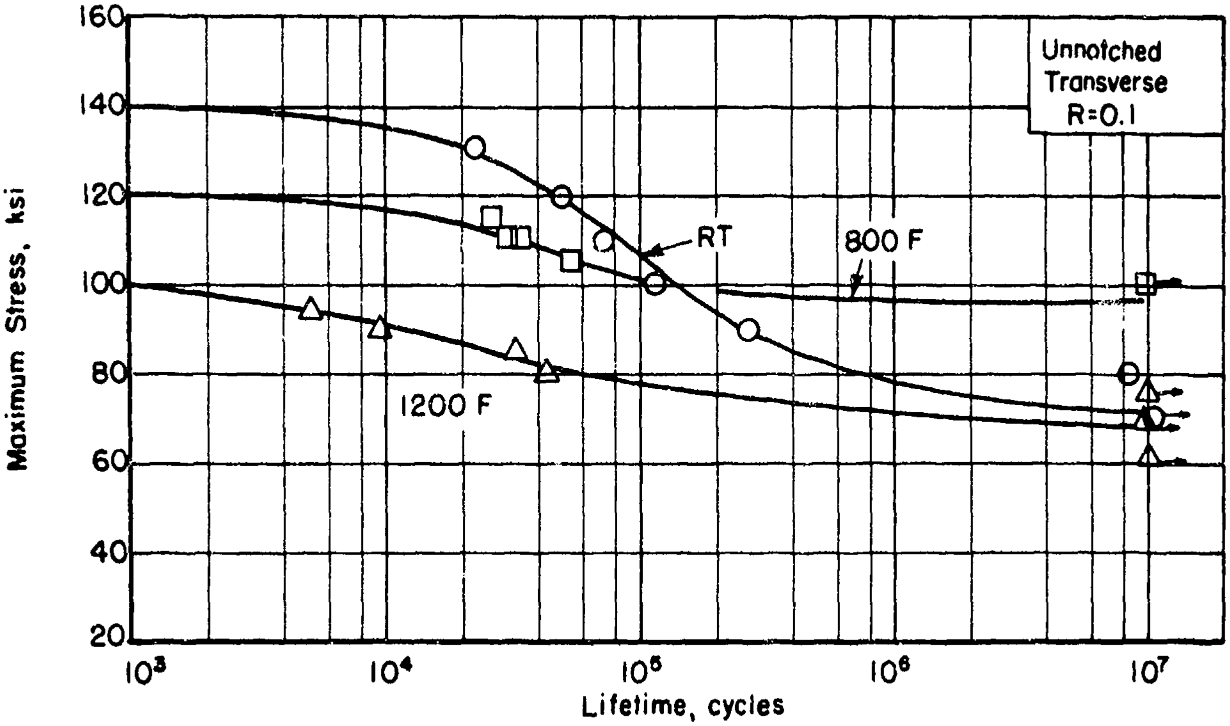

FIGURE 54. AXIAL-LOAD FATIGUE RESULTS FOR UNNOTCHED INCONEL 625 SHEET

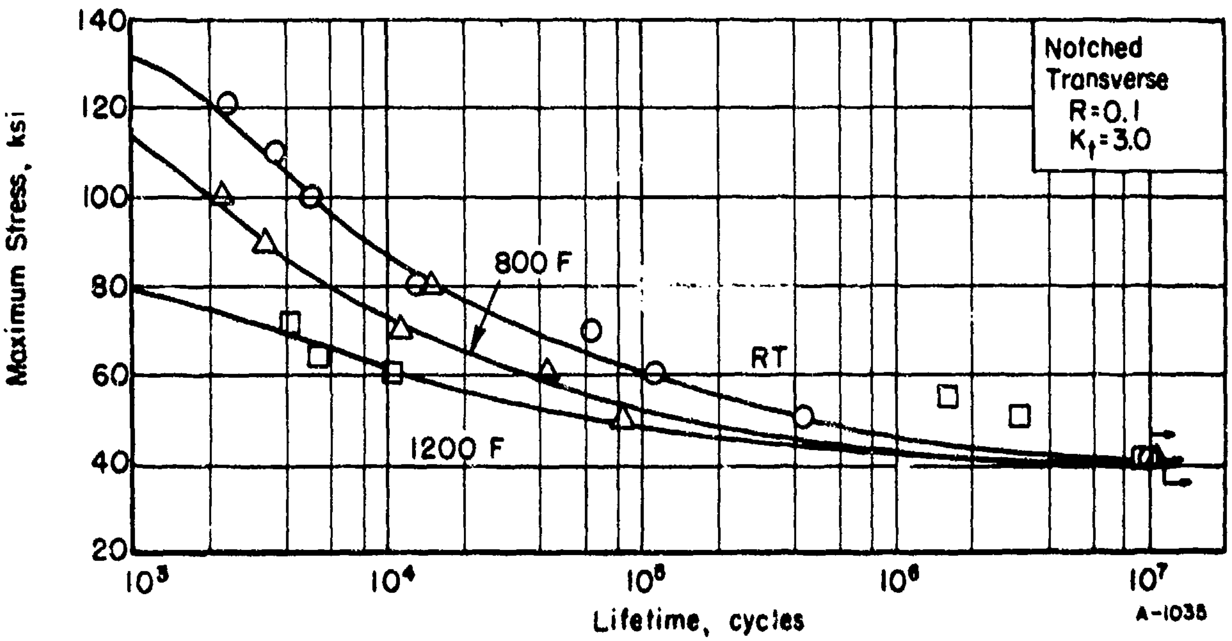

FIGURE 55. AXIAL-LOAD FATIGUE RESULTS FOR NOTCHED (K_t = 3.0) INCONEL 625 SHEET

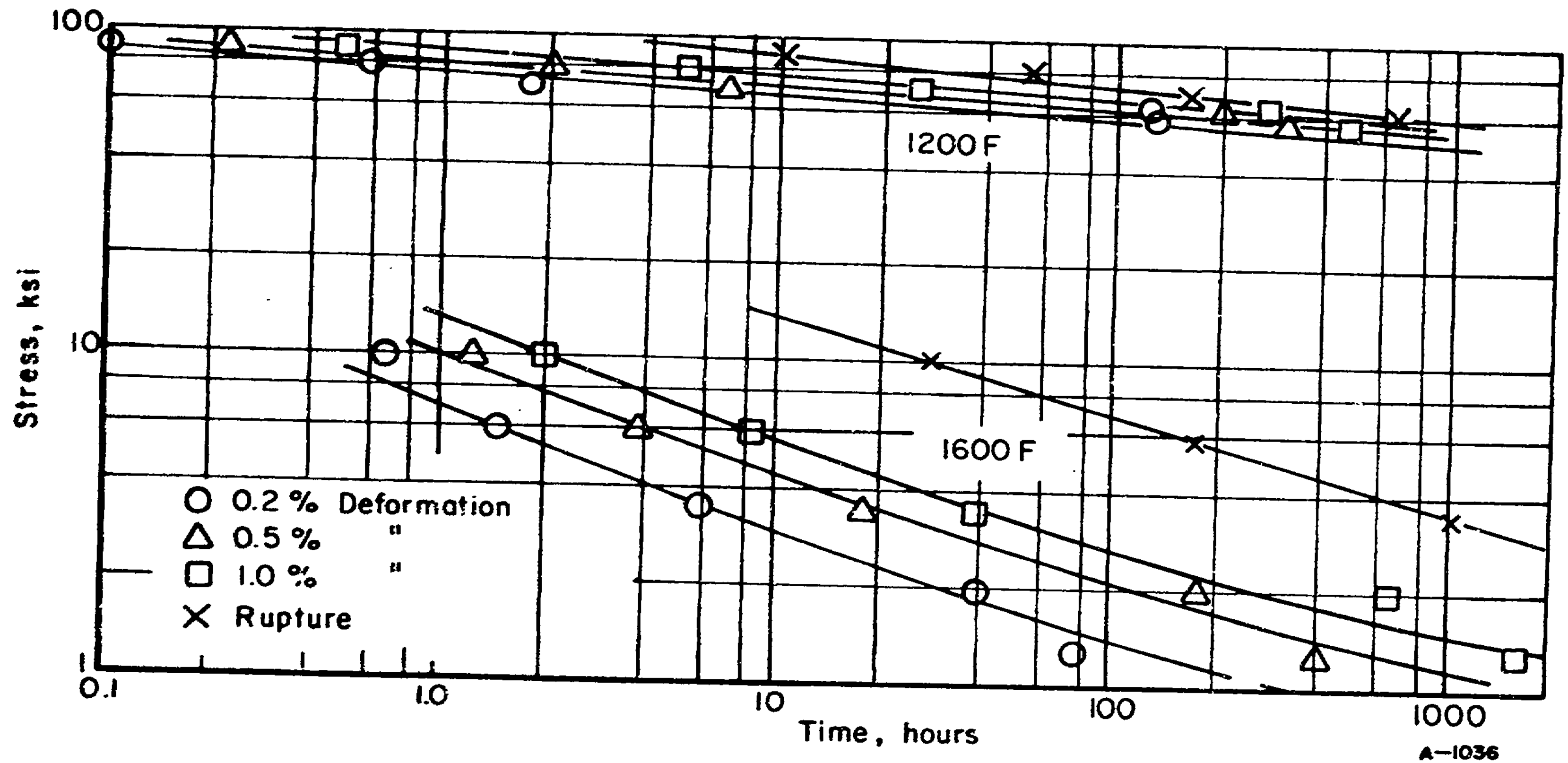

FIGURE 56. STRESS-RUPTURE AND PLASTIC DEFORMATION CURVES FOR INCONEL 625 SHEET

HA-188 Alloy

Material Description

Haynes Alloy 188 is a new cobalt-base alloy development of the Stellite Division of the Cabot Corporation. It is reported to have excellent high-temperature strength and oxidation resistance, and good post-aging ductility. It can be strengthened and hardened by cold work. The alloy can be welded by conventional techniques and exhibits good restraint-welding characteristics. Studies are currently in progress to define the aging characteristics of this alloy.

The composition of this material is as follows:

Chemical Composition	Percent
Chromium	22.3
Tungsten	13.6
Carbon	0.13
Nickel	22.0
Silicon	0.28
Manganese	0.69
Iron	2.0
Phosphorus	0.013
Sulfur	0.003
Cobalt	Balance

This alloy was obtained as 0.078-inch x 36-inch x 96-inch sheet.

Processing and Heat Treating

The specimen layout for HA-188 is presented in Figure 57. Testing was conducted in the as-received annealed and pickled condition.

Test Results

Tension. Results of longitudinal and transverse tests at room temperature, 600 F, 1000 F, and 1400 F are presented in Table XXV. Stress-strain

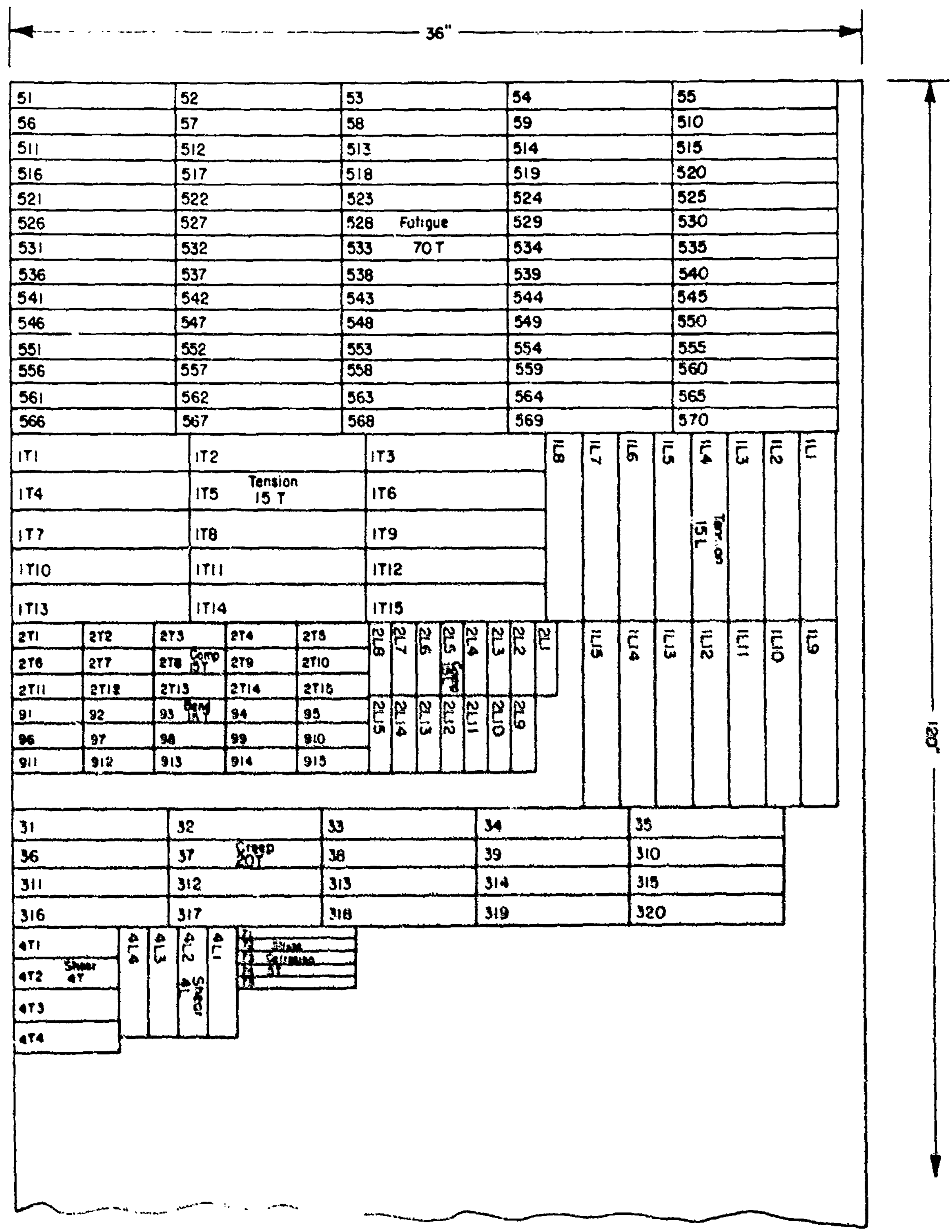

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FIGURE 57. SPECIMEN LAYOUT FOR HA-188 SHEET

curves at temperature are shown in Figures 58 and 59. Effect-of-temperature curves are presented in Figure 62.

Compression. Results of longitudinal and transverse tests at room temperature, 600 F, 1000 F, and 1400 F are given in Table XXVI. Compressive stress-strain and tangent-modulus curves at temperature are shown in Figures 60 and 61. Effect-of-temperature curves are shown in Figure 63.

Shear. Results of room-temperature tests in the longitudinal and transverse directions are given in Table XXVII.

Bend. Bend test data are given in the "data sheet" in the conclusions section of this report.

Fracture Toughness. Tests were performed on specimens of full sheet thickness x 18 inches x 48 inches. Average K_c was 175 ksi$\sqrt{\text{in.}}$ The net section yield stress at fracture was greater than the tensile yield strength of the material. Therefore, the K_c values are considered not valid.

Fatigue. Axial-load tests were conducted on unnotched and notched specimens at room temperature, 1000 F, and 1400 F. Results are given in tabular form in Tables XXVIII and XXIX. S-N curves are shown in Figures 64 and 65.

Creep and Stress Rupture. Tests were conducted at 800 F, 1200 F, and 1600 F for transverse specimens. Results are presented in tabular form in Table XXX. Log stress-versus-log time curves are shown in Figure 66.

Stress Corrosion. Tests were conducted as described in the experimental procedure section of this report. No failures or cracks occurred in the 1000-hour test duration.

Thermal Expansion and Density. Values obtained are presented in the "data sheet" in the conclusions section of this report.

TABLE XXV. TENSION TEST RESULTS FOR HA-188 ALLOY SHEET

Specimen Number	Ultimate Tensile Strength, ksi	0.2 Percent Offset Yield Strength, ksi	Elongation in 2 Inches, Percent	Tensile Modulus psi x 10^6
		Longitudinal at Room Temperature		
1L1	146.0	77.6	60.0	35.3
1L2	146.0	79.4	60.0	34.9
1L3	146.0	78.5	59.5	35.0
		Transverse at Room Temperature		
1T1	145.0	68.0	60.0	36.6
1T2	146.0	69.5	59.5	32.6
1T3	145.5	68.8	59.8	34.5
		Longitudinal at 600F		
1L4	128.0	55.3	66.0	37.9
1L5	129.0	55.2	61.0	34.9
1L6	128.6	55.2	63.6	36.3
		Transverse at 600F		
1T4	128.0	49.0	66.5	31.4
1T5	127.0	49.0	60.5	34.9
1T6	127.6	49.0	63.7	33.0
		Longitudinal at 1000F		
1L7	119.5	51.4	55.5	33.8
1L8	120.0	51.3	57.5	27.3
1L9	119.0	51.3	56.4	30.6
		Transverse at 1000F		
1T7	118.0	45.3	54.0	33.4
1T8	118.0	46.1	59.0	32.4
1T9	118.1	45.6	56.4	31.6

TABLE XXV. (Concluded)

Specimen Number	Ultimate Tensile Strength, ksi	0.2 Percent Offset Yield Strength, ksi	Elongation in 2 Inches, Percent	Tensile Modulus, psi x 10^6
		Longitudinal at 1400F		
1L10	69.3	46.6	51.0	25.4
1L11	70.9	47.2	50.0	27.2
1L12	70.0	47.0	50.4	26.2
		Transverse at 1400F		
1T10	71.8	43.7	45.5	24.9
1T11	69.6	44.7	52.0	24.1
1T12	70.6	44.1	48.8	23.6

TABLE XXVI. COMPRESSION TEST RESULTS FOR HA-188 SHEET

Specimen No.	0.2 Percent Offset Yield Strength, ksi	Compression Modulus, psi x 10^6
Longitudinal at Room Temperature		
2L1	49.8	(a)
2L2	50.6	33.2
2L3	49.8	33.2
Transverse at Room Temperature		
2T1	73.6	33.2
2T2	73.7	32.7
2T3	74.1	33.0
Longitudinal at 600 F		
2L4	43.5	31.2
2L5	43.2	29.0
2L6	43.8	30.0
Transverse at 600 F		
2T4	54.8	31.4
2T5	54.6	28.5
2T6	53.2	28.6
Longitudinal at 1000 F		
2L7	40.6	32.4
2L8	41.5	28.9
2L9	41.8	29.8
Transverse at 1000 F		
2T7	48.0	26.8
2T8	49.5	30.2
2T9	50.9	30.1

TABLE XXVI. (Concluded)

Specimen No.	0.2 Percent Offset Yield Strength, ksi	Compression Modulus, psi x 10^6
	Longitudinal at 1400 F	
2L10	43.9	24.4
2L11	(b)	(b)
2L12	44.6	24.6
	Transverse at 1400 F	
2T10	47.5	25.6
2T11	45.2	24.6
2T12	45.8	27.1

(a) Load-strain curve not suitable for modulus determination.

(b) Specimen accidentally overloaded.

TABLE XXVII. SHEAR TEST RESULTS FOR HA-188 SHEET AT ROOM TEMPERATURE

Specimen No.	Ultimate Shear Strength, ksi
	Longitudinal
4L-1	134.5
4L-2	133.0
4L-3	132.0
4L-4	131.0
	Transverse
4T-1	131.5
4T-2	131.0
4T-3	138.0
4T-4	141.0

TABLE XXVIII. AXIAL-LOAD FATIGUE TEST RESULTS FOR UNNOTCHED HA-188 SHEET AT A STRESS RATIO OF R = 0.1

Specimen No.	Maximum Stress, ksi	Lifetime, cycles
	Room Temperature	
515	160	10
516	145	860
519	140	25,928
514	130	50,220
520	120	83,140
517	110	138,950
513	100	322,340
521	90	775,600
518	80	10,317,300[a]
	1000 F	
59	100	90,490
58	90	164,110
510	90	90,820
512	80	16,280,100[a]
57	70	6,657,800
	1400 F	
53	70	90
54	60	13,700
55	55	17,100
56	55	38,270
52	50	1,660,650

(a) Did not fail.

TABLE XXIX. AXIAL-LOAD FATIGUE TEST RESULTS FOR NOTCHED (K_t = 3.0) HA-188 SHEET AT A STRESS RATIO OF R = 0.1

Specimen No.	Maximum Stress, ksi	Lifetime, cycles
	Room Temperature	
561	140	263
563	120	4,099
562	100	12,130
567	90	22,200
560	80	45,570
566	70	89,100
564	60	197,700
565	50	1,198,100[a]
568	40	12,591,400[a]
	1000 F	
569	90	5,270
554	90	2,756
536	80	4,277
556	70	27,090
555	70	27,990
558	60	87,600
557	50	6,018,100[a]
559	40	10,241,200[a]
	1400 F	
553	70	390
548	60	2,700
552	50	4,330
547	45	20,800
550	40	57,300
546	35	51,900[a]
551	30	10,471,700[a]

(a) Did not fail.

TABLE XXX. SUMMARY DATA ON CREEP AND RUPTURE PROPERTIES OF HA-188 SHEET

Specimen No.	Stress, ksi	Temp, F	Hours to Indicated Creep Deformation, percent 0.1	0.2	0.5	1.0	2.0	Initial Strain, percent	Rupture Time, hr	Elongation in 2 Inches, percent	Minimum Creep Rate, percent/hr
34	117.5	800	--	--	--	--	--	--	On loading	55.1	--
36	115.0	800	--	--	--	--	--	44.727	524.8(b)	44.775	--
32	80.0	1200	--	--	--	--	--	15.28	18.6	27.3	--
31	70.0	1200	2.5	5.0	15.0	30.0	40.0	6.98	59.7	19.8	0.50
33	50.0	1200	12.0	37.0	100.0	190.0	320.0	0.760	1286.6	14.1	0.0045
39	35.0	1200	60.0	190.0	560.0	1185.0(a)	--	0.163	651.2(b)	0.745	0.00081
37	25.0	1600	--	0.02	0.15	0.28	0.65	0.167	7.1	36.1	2.6
35	15.0	1600	1.2	2.5	7.2	15.0	27.0	0.099	152.9	35.5	0.063
38	11.0	1600	8.7	30.0	94.0	197.0	290.0	0.021	928.5	16.3	0.0055
310	7.5	1600	230.0	485.0	1250.0(a)	2500.0(a)	--	0.046	600.1(b)	0.291	0.00039

(a) Estimated.
(b) Test discontinued.

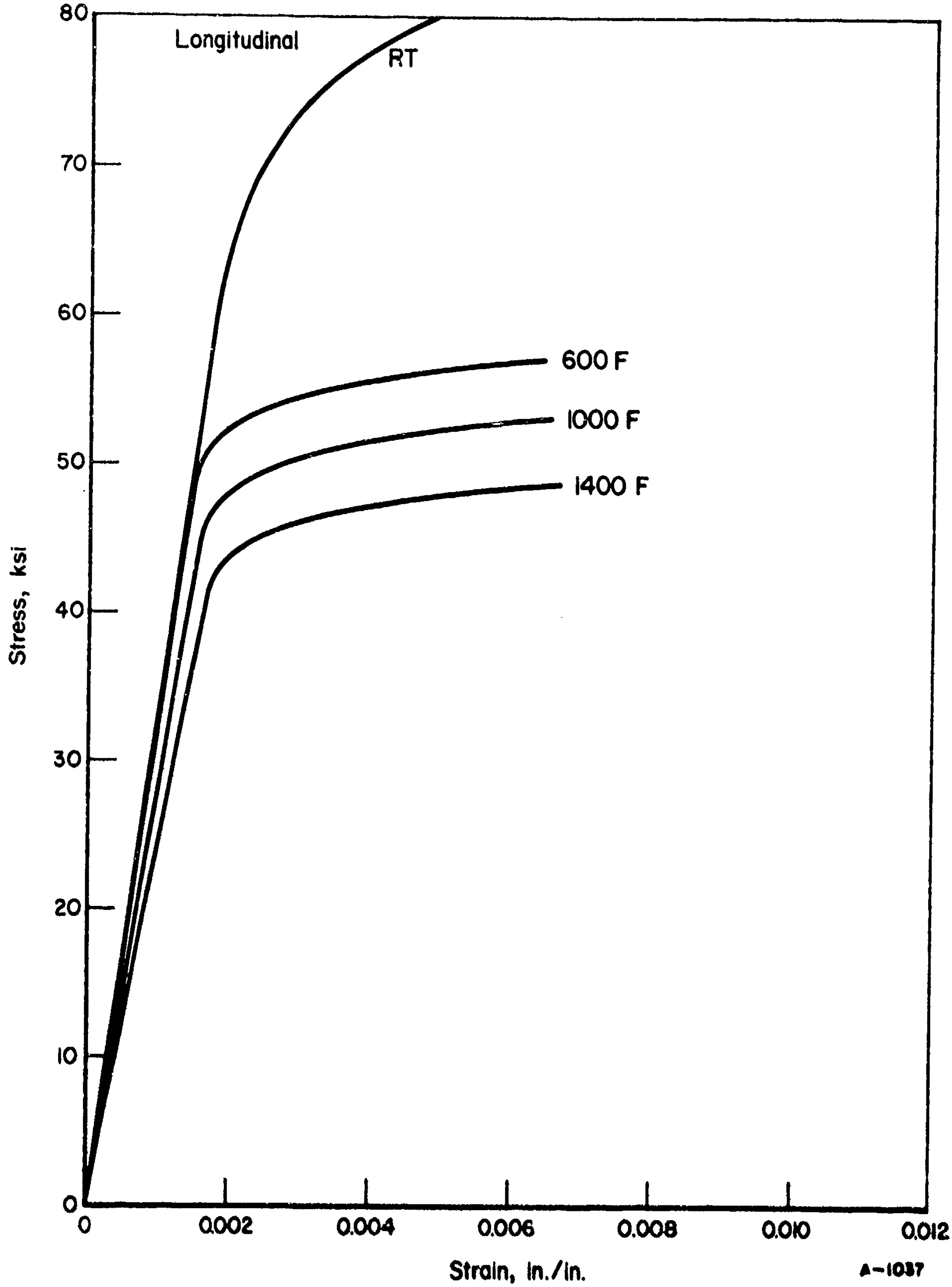

FIGURE 58. TYPICAL TENSILE STRESS-STRAIN CURVES FOR HA-188 SHEET (LONGITUDINAL)

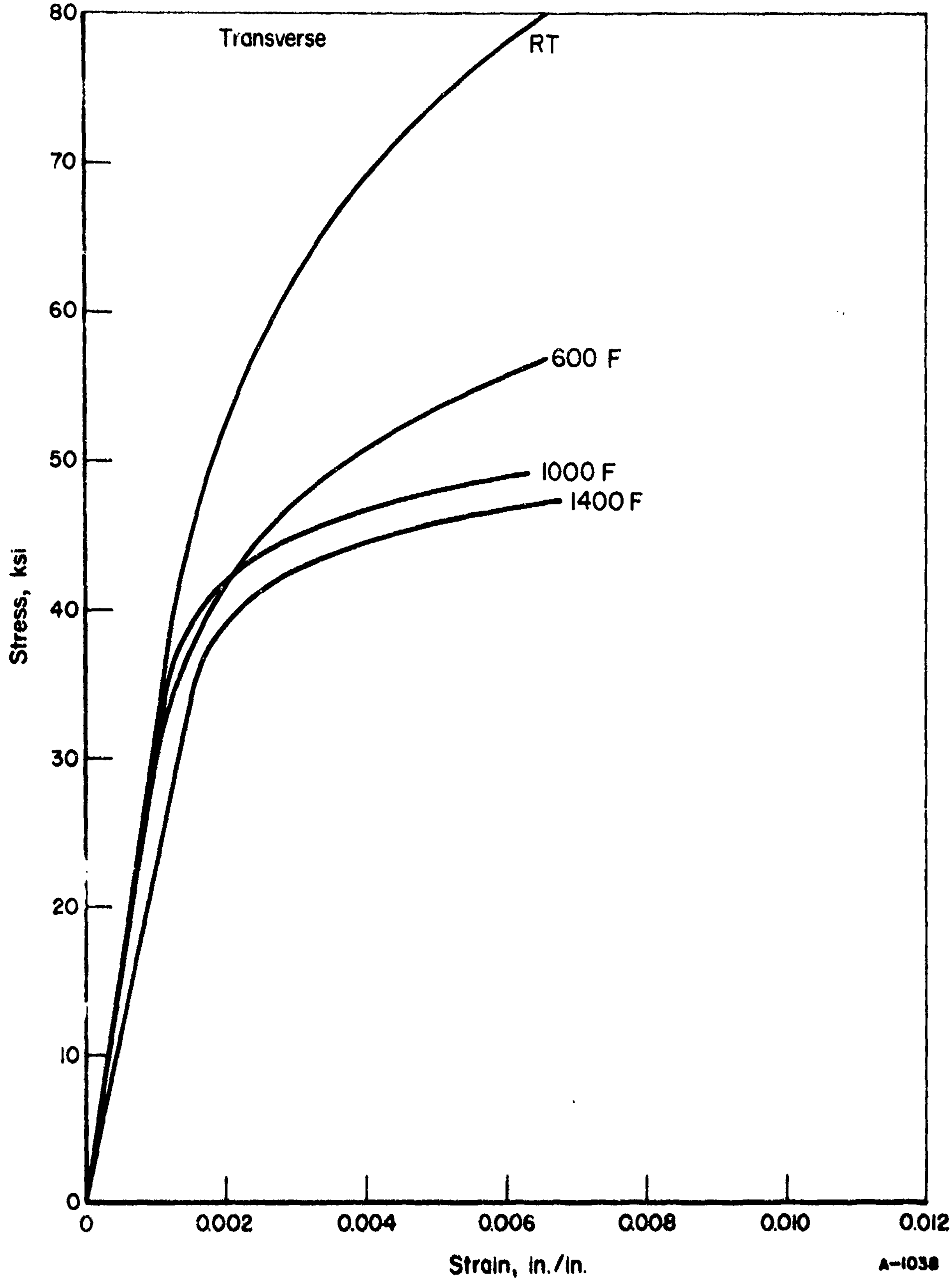

FIGURE 59. TYPICAL TENSILE STRESS-STRAIN CURVES FOR HA-188 SHEET (TRANSVERSE)

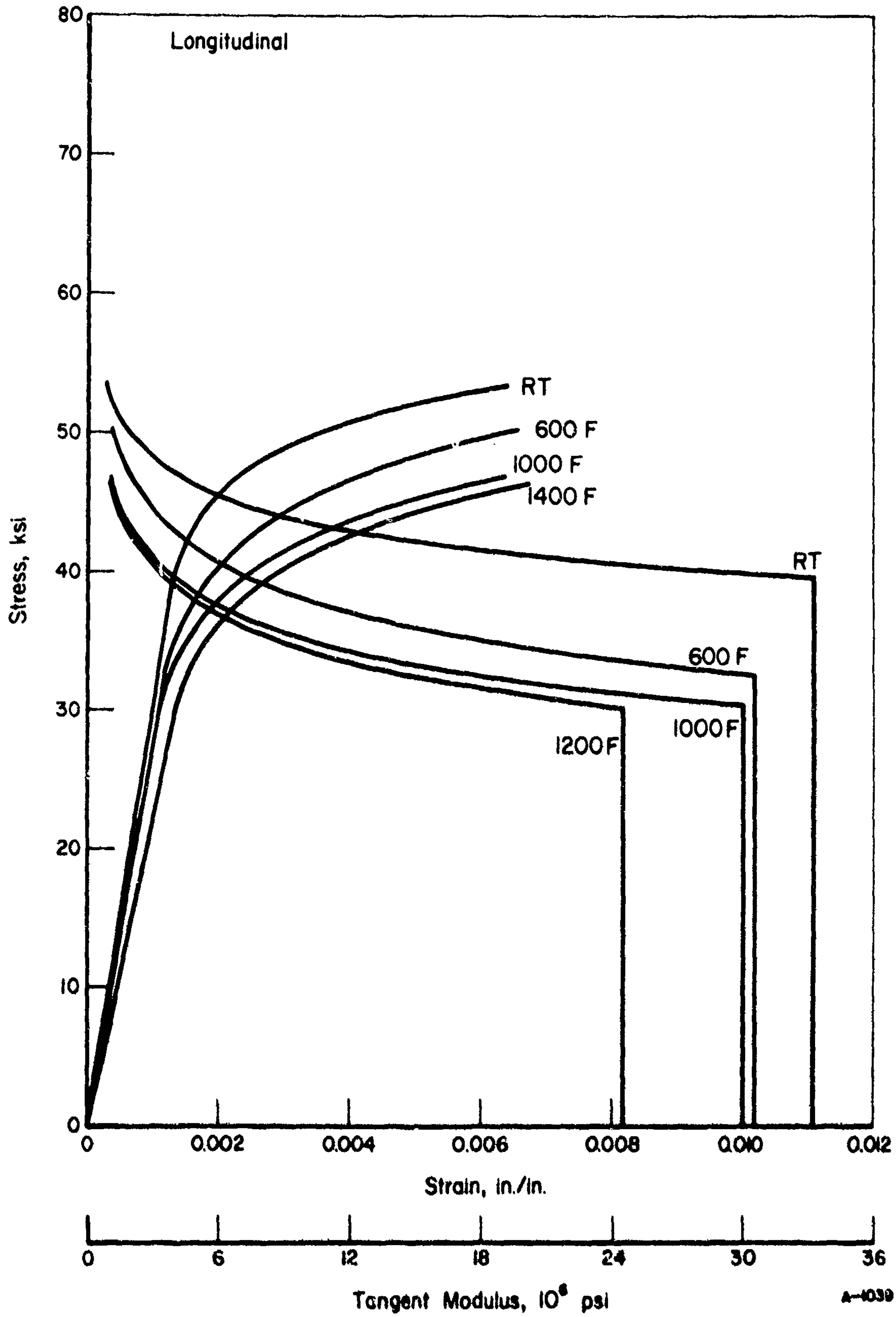

FIGURE 60. TYPICAL COMPRESSION STRESS-STRAIN AND TANGENT MODULUS CURVES FOR HA-188 SHEET (LONGITUDINAL)

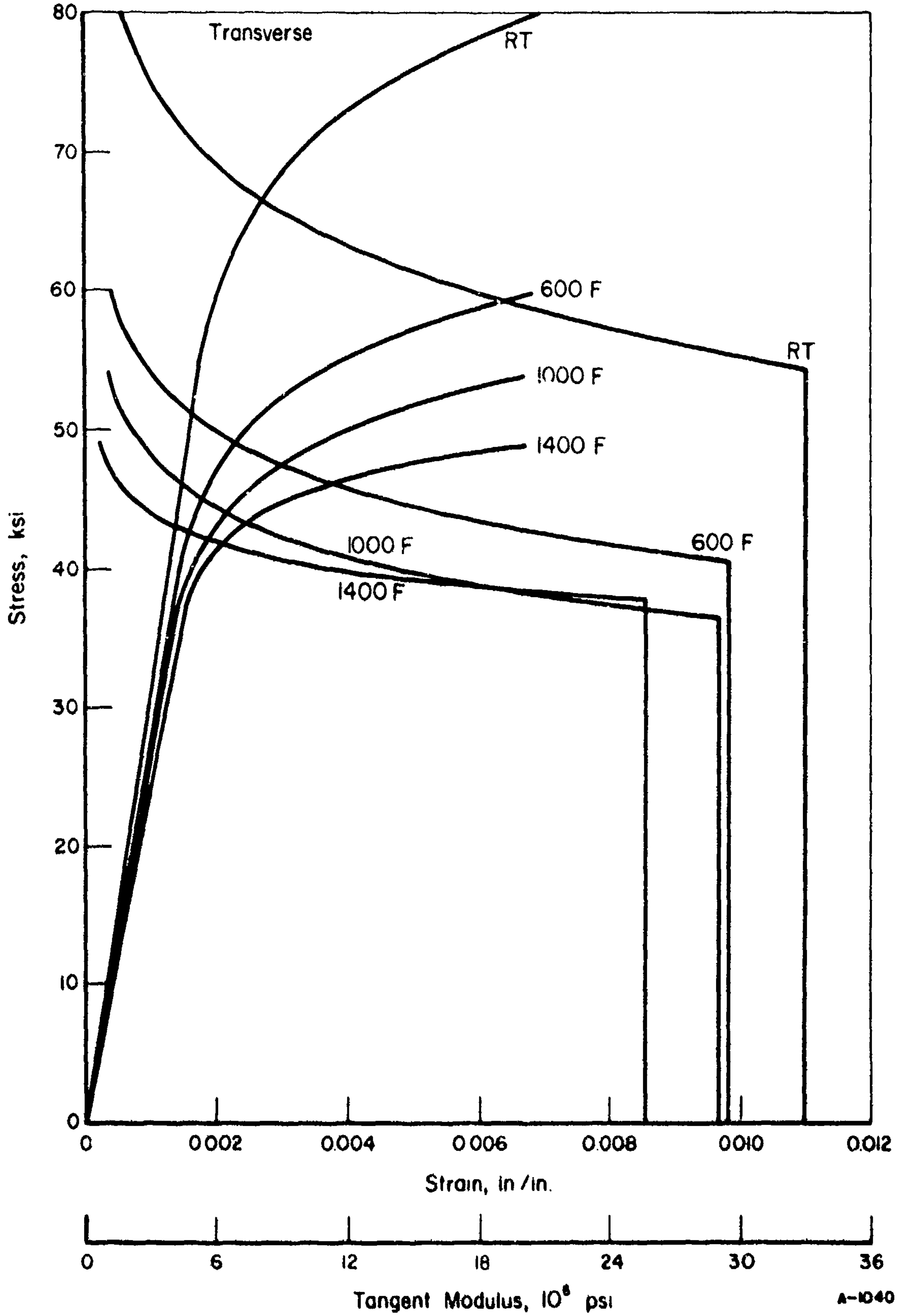

FIGURE 61. TYPICAL COMPRESSION STRESS-STRAIN AND TANGENT MODULUS CURVES FOR HA-188 SHEET (TRANSVERSE)

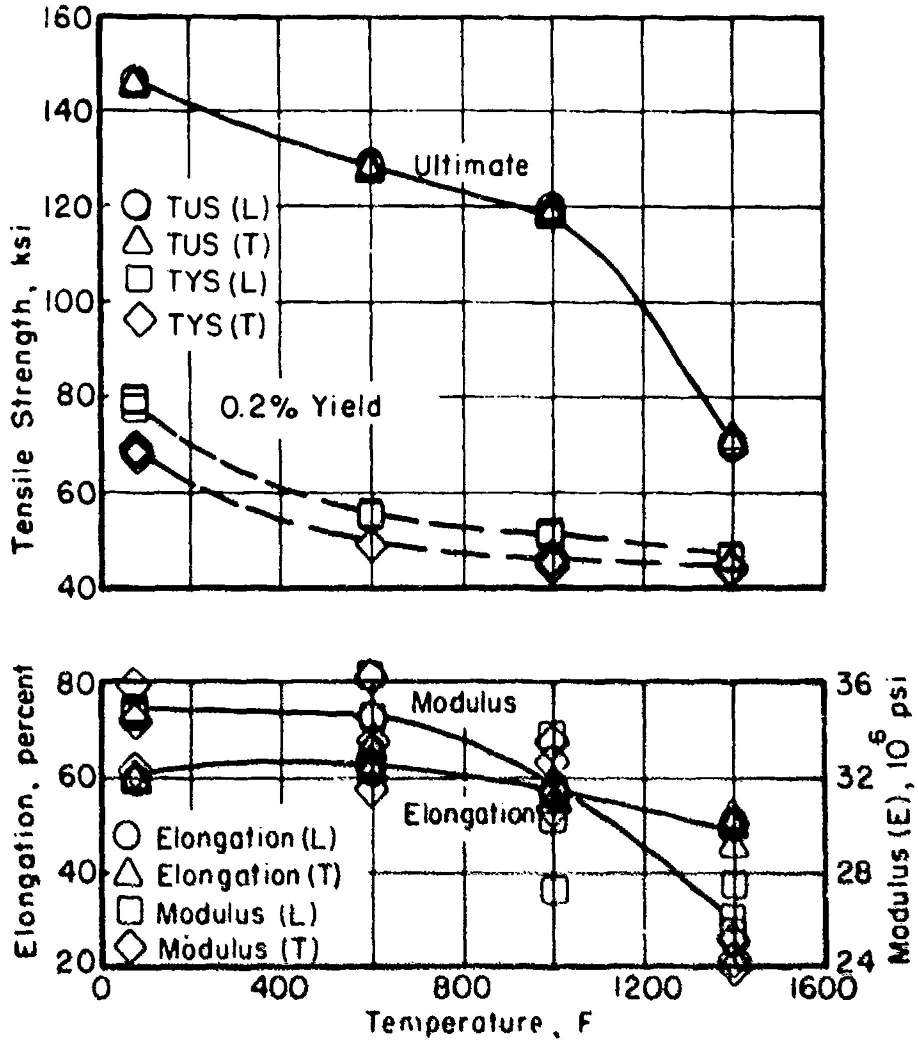

FIGURE 62. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF HA-188 ALLOY SHEET

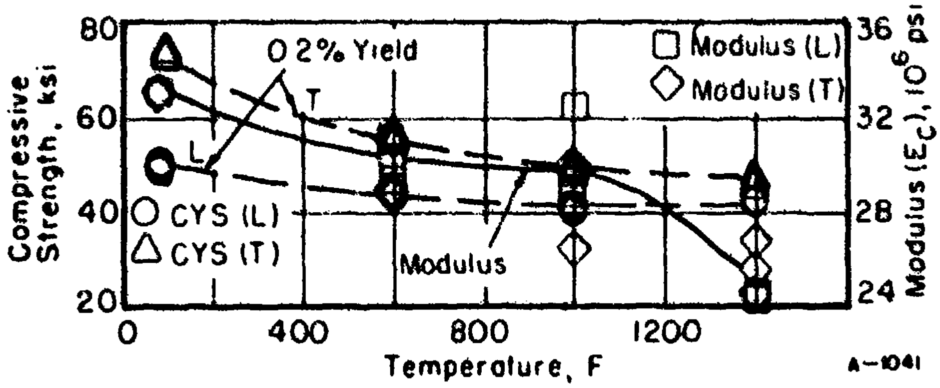

FIGURE 63. EFFECT OF TEMPERATURE ON THE COMPRESSIVE PROPERTIES OF HA-188 ALLOY SHEET

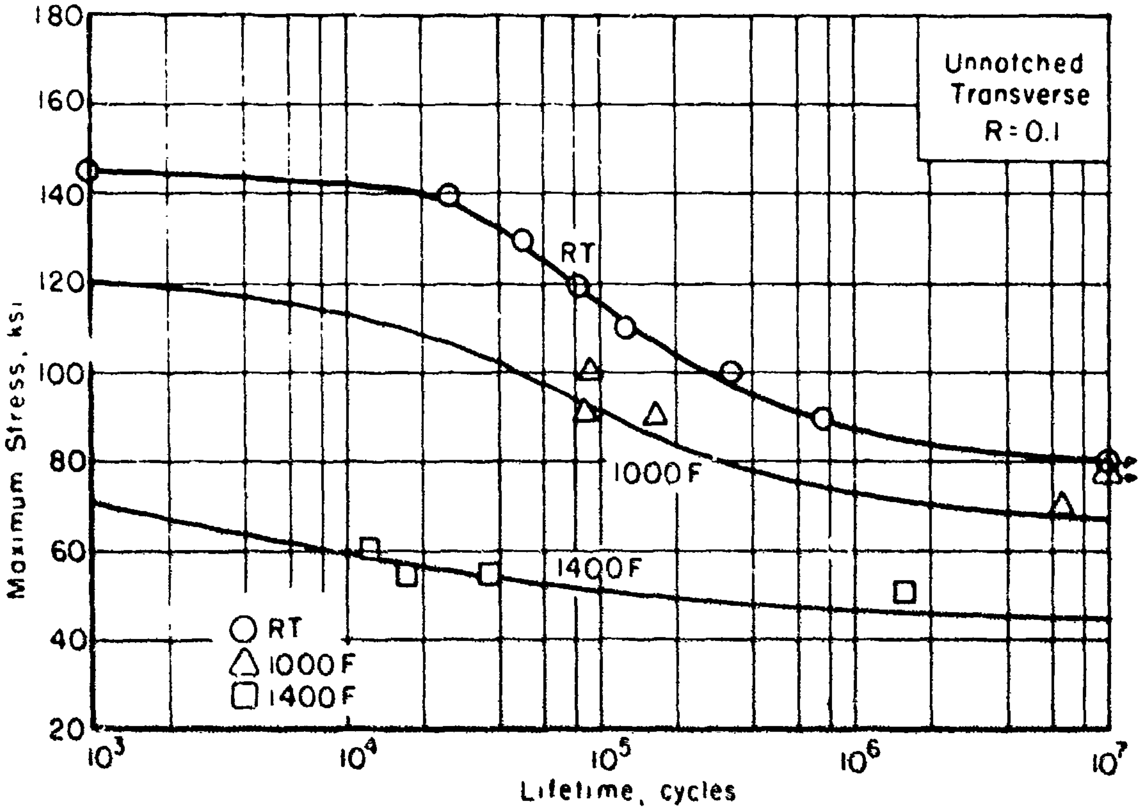

FIGURE 64. AXIAL-LOAD FATIGUE RESULTS FOR UNNOTCHED HA-188 SHEET

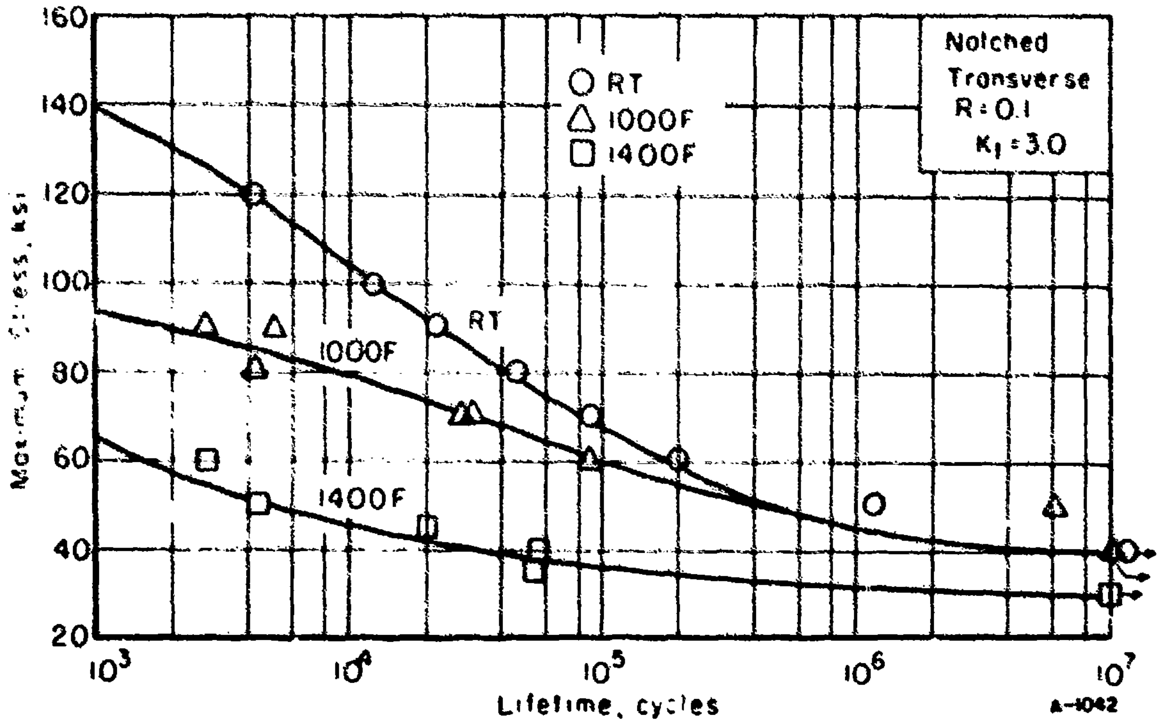

FIGURE 65. AXIAL-LOAD FATIGUE RESULTS FOR NOTCHED (K_t = 3.0) HA-188 SHEET

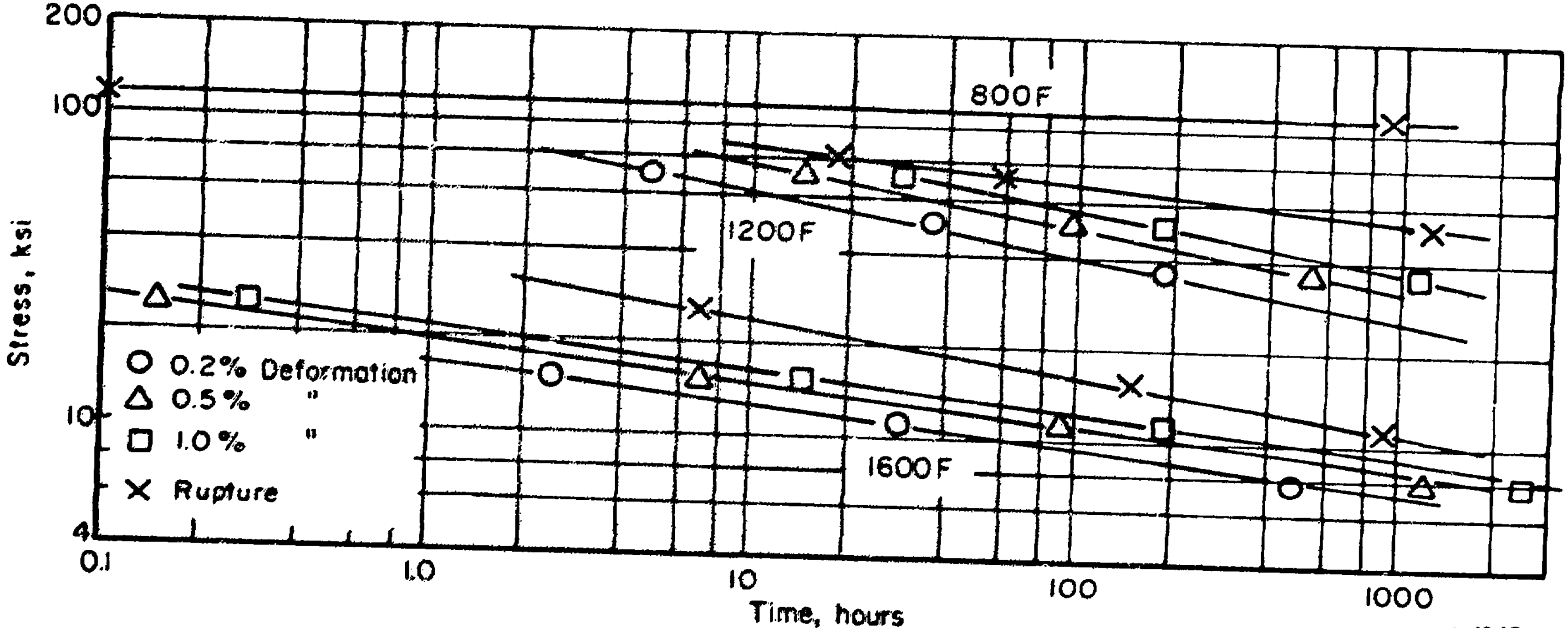

FIGURE 66. STRESS-RUPTURE AND PLASTIC DEFORMATION CURVES FOR HA-188 SHEET

Custom 455 Alloy

Material Description

Custom 455 is a new martensitic age-hardenable stainless steel developed by The Carpenter Research Laboratories of The Carpenter Technology Corporation. The alloy is relatively soft and easily formable in the annealed condition. A simple, single-step aging treatment develops good yield strengths with good ductility and toughness.

Custom 455 can be machined in the annealed condition and welded in the same manner as other stainless steels. It is easily formable because of its low work-hardening rate. The dimensional change during hardening is only about 0.001 in./in. which permits close tolerance finish machining in the annealed state. The alloy is designed to be used where simplicity of heat treatment, ease of fabrication, high strength, and corrosion resistance are required in combination.

The material used in this evaluation was obtained as 3/4-inch round bar with the following composition:

Chemical Composition	Percent
Carbon	0.009
Manganese	0.07
Silicon	0.17
Phosphorus	0.010
Sulfur	0.005
Chromium	11.61
Nickel	8.75
Molybdenum	0.01
Copper	2.15
Titanium	1.19
Columbum + Tantalum	0.23
Iron	Balance

Processing and Heat Treating

No specimen layout is shown since the specimens were all longitudinal, cut from 3/4-inch round bar. The alloy was tested after aging at 950 F for 4 hours and air cooled.

Test Results

Tension. Results of tests in the longitudinal direction at room temperature, 400 F, 600 F, and 800 F are given in tabular form in Table XXXI. Stress-strain curves at temperature are presented in Figure 67. Effect-of-temperature curves are presented in Figure 69.

Compression. Results of longitudinal tests at room temperature, 400 F, 600 F, and 800 F are presented in tabular form in Table XXXII. Compressive stress-strain and tangent-modulus curves at temperature are shown in Figure 68. Effect-of-temperature curves are shown in Figure 70.

Shear. Results of pin-shear type tests at room temperature are presented in Table XXXIII.

Impact. Results of Charpy V-notch tests at room temperature and -90 F are given in the "data sheet" in the conclusions section of this report.

Fracture Toughness. Results of slow-bend Chevron-notched-type tests are given in Table XXXIV. Average K_{Ic} was 55.8 ksi$\sqrt{in.}$ This number is considered valid.

Fatigue. Axial-load tests were conducted at room temperature, 400 F, and 800 F for unnotched and notched specimens. Tabular test results are given in Tables XXXV and XXXVI. S-N curves are presented in Figures 71 and 72.

Creep and Stress Rupture. Tests were conducted at 400 F, 600 F, and 850 F. Results are presented in tabular form in Table XXXVII. Log stress-versus-log time curves are shown in Figure 73.

Stress Corrosion. Tests were conducted as described in the experimental procedures section of this report. No failures or cracks occurred during the 1000-hour test duration.

Thermal Expansion and Density. Values obtained are presented in the "data sheet" in the conclusions section of this report.

TABLE XXXI. TENSION TEST RESULTS FOR CUSTOM 455 ROUND BAR

Specimen No.	Ultimate Tensile Strength, ksi	0.2 Percent Offset Yield Strength, ksi	Elongation in 2 Inches, percent	Reduction in Area, percent	Tensile Modulus, psi x 10^6
			Longitudinal at Room Temperature		
1L1	248.3	247.7	10.0	46.1	27.8
1L2	249.0	247.7	10.0	44.9	28.3
1L3	247.8	246.8	10.0	45.1	28.8
			Longitudinal at 400 F		
1L4	217.7	216.0	10.5	49.3	27.5
1L5	213.7	211.5	10.7	51.6	28.3
1L6	216.3	215.7	10.5	49.2	27.7
			Longitudinal at 600 F		
1L7	201.5	197.2	11.5	54.8	26.6
1L8	201.7	198.7	12.0	52.9	26.8
1L9	200.3	195.6	11.5	54.8	26.6
			Longitudinal at 800 F		
1L10	181.4	174.3	14.0	63.0	24.6
1L11	180.5	174.3	15.0	63.0	24.5
1L12	180.0	173.7	15.0	63.5	24.4

TABLE XXXII. COMPRESSION TEST RESULTS FOR CUSTOM 455 ROUND BAR

Specimen No.	0.2 Percent Offset Yield Strength, ksi	Compression Modulus, psi x 10^6
Longitudinal at Room Temperature		
2L1	256.0	29.8
2L2	255.0	29.7
2L3	255.0	29.7
Longitudinal at 400 F		
2L4	221.0	27.6
2L5	220.0	27.9
2L6	214.0	27.7
Longitudinal at 600 F		
2L7	202.0	26.9
2L8	202.0	26.5
2L9	202.0	26.1
Longitudinal at 800 F		
2L10	179.0	23.6
2L11	177.0	23.4
2L12	174.0	24.6

TABLE XXXIII. SHEAR TEST RESULTS FOR CUSTOM 455 ROUND BAR AT ROOM TEMPERATURE

Specimen No.	Ultimate Shear Strength, ksi
4L1	152.0
4L2	152.0
4L3	152.0
4L4	152.0

TABLE XXXIV. FRACTURE TOUGHNESS TEST RESULTS FOR CUSTOM 455 ROUND BAR

Specimen No.	Thickness, in.	Width, in.	Crack Length, in.	Span, in.	K_{Ic}, ksi$\sqrt{in.}$
61	0.324	0.650	0.302	2.6	57.4
62	0.3245	0.650	0.320	2.6	54.9
63	0.3245	0.650	0.316	2.6	53.2
64	0.3245	0.650	0.308	2.6	56.5
65	0.3248	0.6492	0.340	2.6	57.1
66	0.325	0.650	0.311	2.6	50.6

TABLE XXXV. AXIAL-LOAD FATIGUE TEST RESULTS FOR UNNOTCHED CUSTOM 455 BAR AT A STRESS RATIO OF R = 0.1

Specimen No.	Maximum Stress, ksi	Lifetime, cycles
	Room Temperature	
53	240	4,660
52	230	4,790
51	220	9,989
54	210	12,910
55	200	8,010
56	190	13,310
57	180	26,660
58	170	19,000
59	150	23,240
510	130	94,600
511	120	15,117,500[(a)]
	400 F	
522	240	10
521	220	2,080
513	200	6,860
514	190	5,350
515	180	4,380
516	160	37,600
517	150	27,600
518	130	64,500
519	120	67,100[(b)]
520	120	10,069,800[(a)]
	800 F	
526	180	2,600
531	160	8,300
523	150	55,900
532	140	239,900
524	130	64,400[(b)]
525	130	1,004,100
528	120	816,800
529	110	1,663,400

(a) Did not fail.
(b) Failed at thermocouple.

TABLE XXXVI. AXIAL-LOAD FATIGUE TEST RESULTS FOR NOTCHED ($K_t = 3.0$) CUSTOM 455 BAR AT A STRESS RATIO OF R = 0.1

Specimen No.	Maximum Stress, ksi	Lifetime, cycles
	Room Temperature	
538	140	2,460
539	120	2,650
533	100	5,510
534	80	10,430
535	60	51,960
536	40	138,020
537	30	15,099,400 [a]
	400 F	
540	120	2,190
541	100	5,530
544	90	8,880
542	80	29,000
545	70	23,700
543	60	3,375,600
546	50	4,663,600
547	40	10,436,600 [a]
	800 F	
550	120	1,980
549	100	4,690
548	80	6,300
552	70	35,890
551	60	725,190
553	50	1,412,900
554	40	10,331,600 [a]

(a) Did not fail.

TABLE XXXVII. SUMMARY DATA ON CREEP AND RUPTURE PROPERTIES FOR CUSTOM 455 ROUND BAR

Spec. No.	Stress, ksi	Temp, F	Hours to Indicated Creep Deformation, percent 0.1	0.2	0.5	1.0	2.0	Initial Strain, percent	Rupture Time, hr	Elongation in 2 in., percent	Reduction of Area, percent	Minimum Creep Rate, percent/hr
35	218.0	400	--	--	--	--	--	--	On loading	8.3	58.9	--
312	215.0	400	--	--	--	--	--	1.562	0.01	9.6	50.9	--
37	210.0	400	0.2	18.0	5000.0(a)	--	--	1.052	815.2(b)	1.359	--	0.000045
314	200.0	400	900.0	6300.0(a)	--	--	--	0.913	764.4(b)	1.003	--	--
313	212.5	600	--	--	--	--	--	--	On loading	8.9	53.7	--
39	200.0	600	0.03	0.05	0.17	0.7	2.6	1.488	5.0	10.4	49.7	0.48
39	190.0	600	0.12	0.55	7.0	30.0	105.0	0.978	375.2	8.9	11.4	0.012
33	175.0	600	5.0	24.0	195.0	990.0	2640.0(a)	0.722	959.2(b)	1.714	--	0.00061
311	160.0	600	57.0	250.0	1750.0(a)	4700.0(a)	--	0.722	794.9(b)	1.041	--	0.00017
32	125.0	850	0.07	0.18	0.6	1.9	4.3	0.641	12.9	20.7	66.3	0.42
31	100.0	850	0.35	0.85	4.6	13.7	31.0	0.492	92.8	20.0	66.2	0.055
34	80.0	850	0.60	3.2	30.0	77.0	188.0	0.403	656.1	35.6	64.0	0.009
36	50.0	850	12.0	65.0	600.0(a)	2100.0(a)	--	0.267	409.1(b)	0.707	--	0.00035
310	35.0	850	38.0	250.0	--	--	--	0.263	455.2(b)	0.522	--	--

(a) Estimated.
(b) Test discontinued.

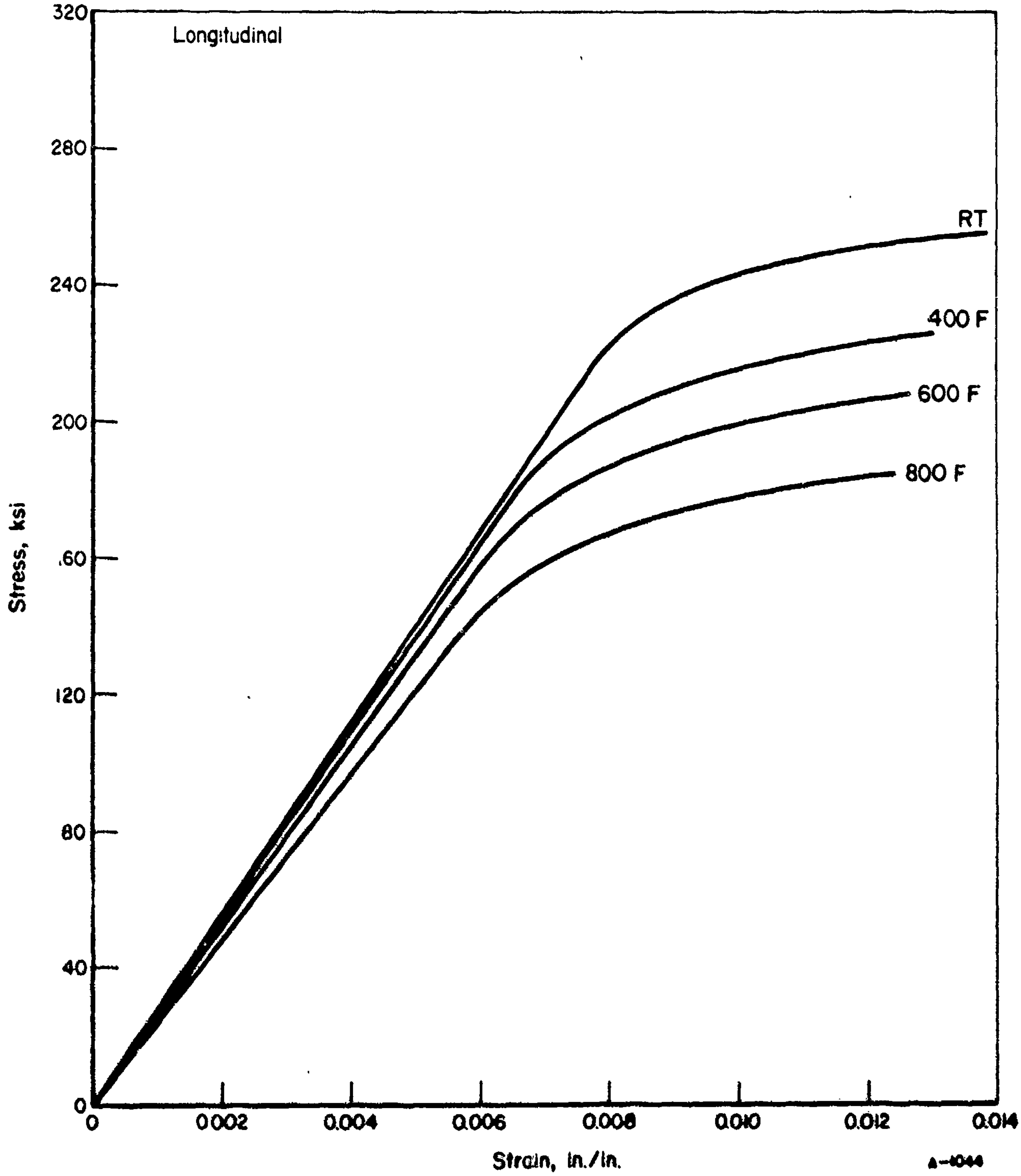

FIGURE 67. TYPICAL TENSILE STRESS–STRAIN CURVES FOR CUSTOM 455 ROUND BAR (LONGITUDINAL)

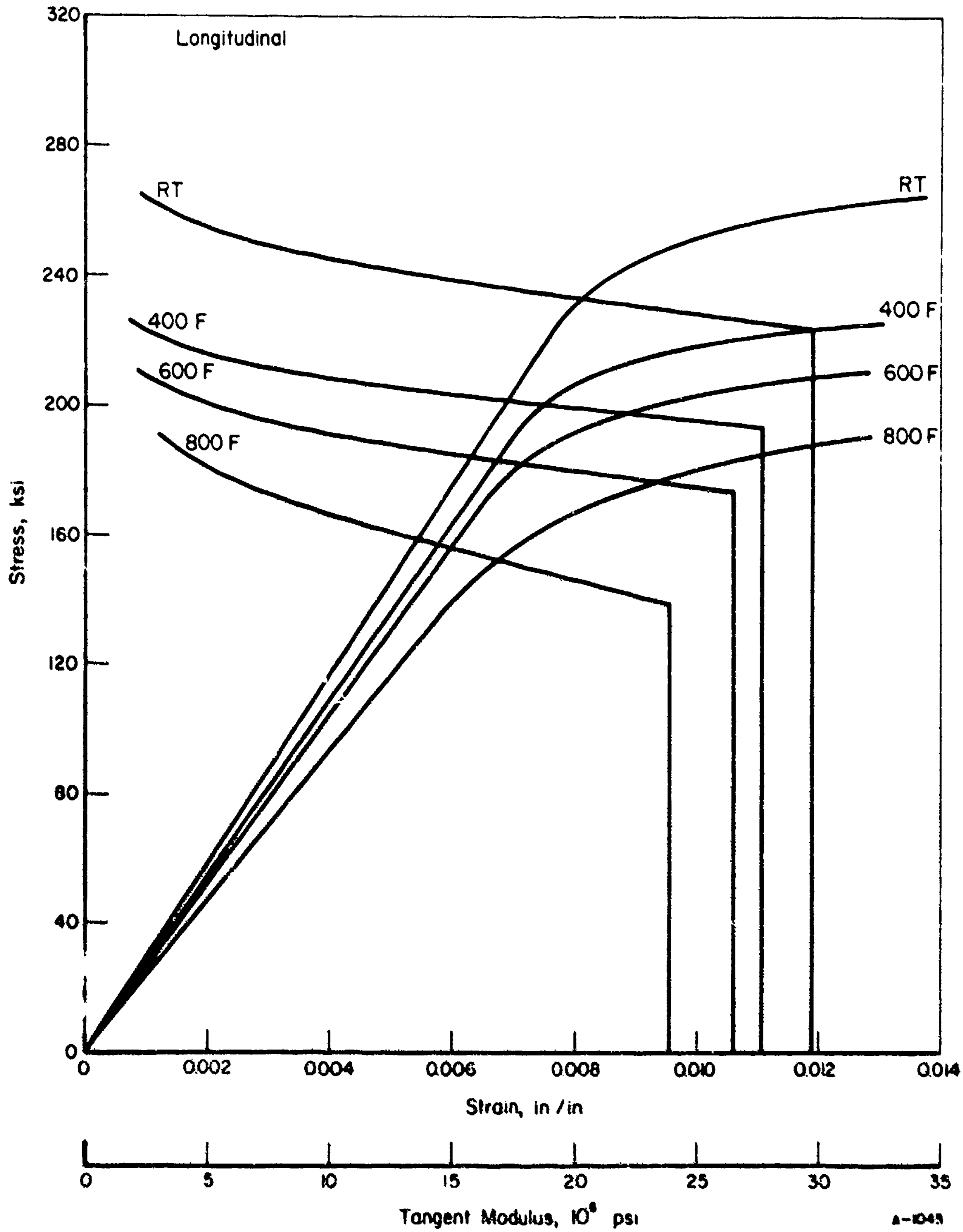

FIGURE 68. TYPICAL COMPRESSION STRESS-STRAIN AND TANGENT MODULUS CURVES FOR CUSTOM 455 ROUND BAR (LONGITUDINAL)

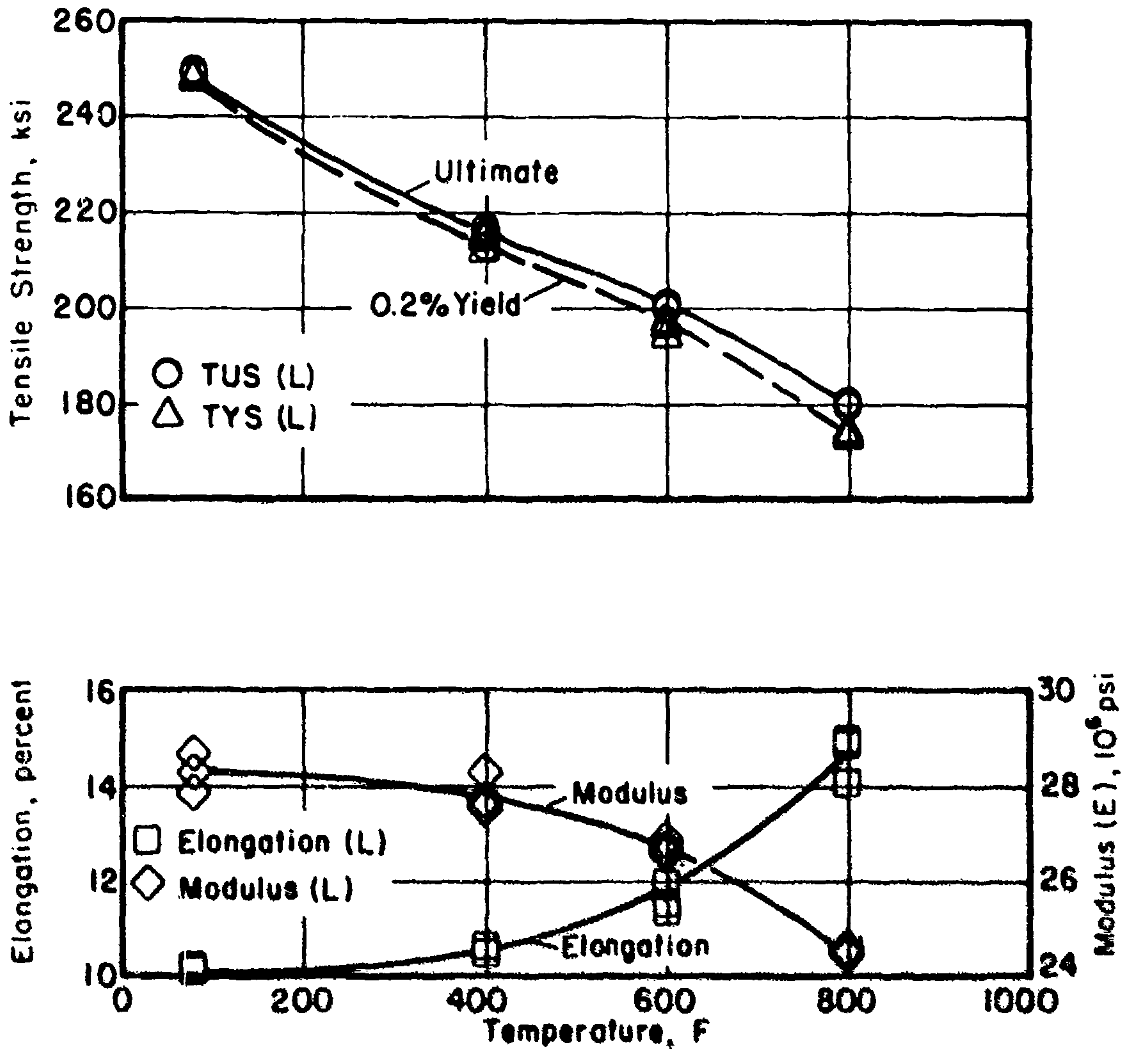

FIGURE 69. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF CUSTOM 455 ROUND BAR

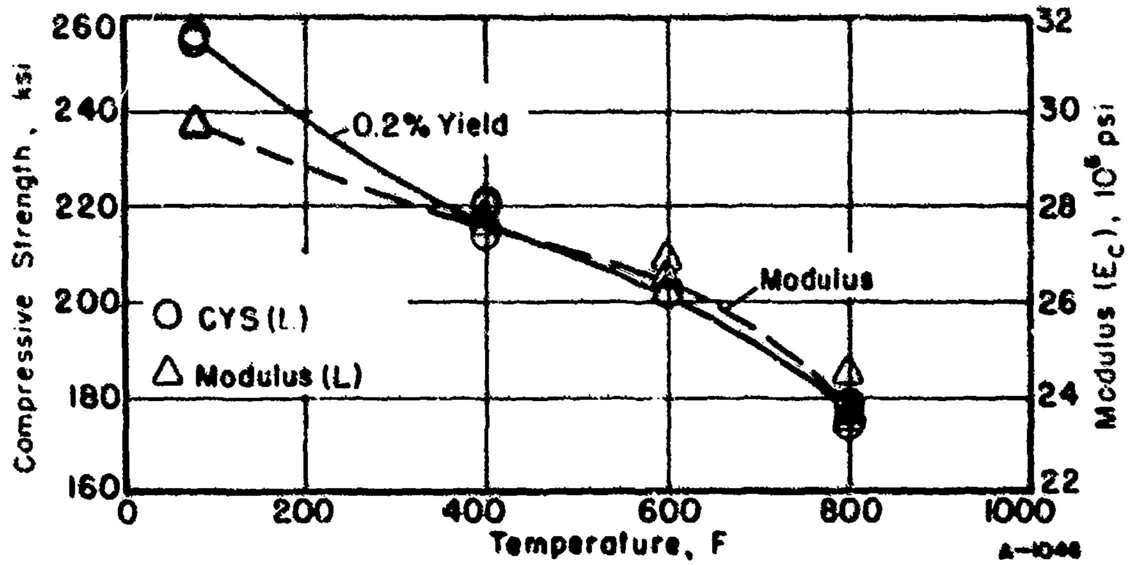

FIGURE 70. EFFECT OF TEMPERATURE ON THE COMPRESSIVE PROPERTIES OF CUSTOM 455 ROUND BAR

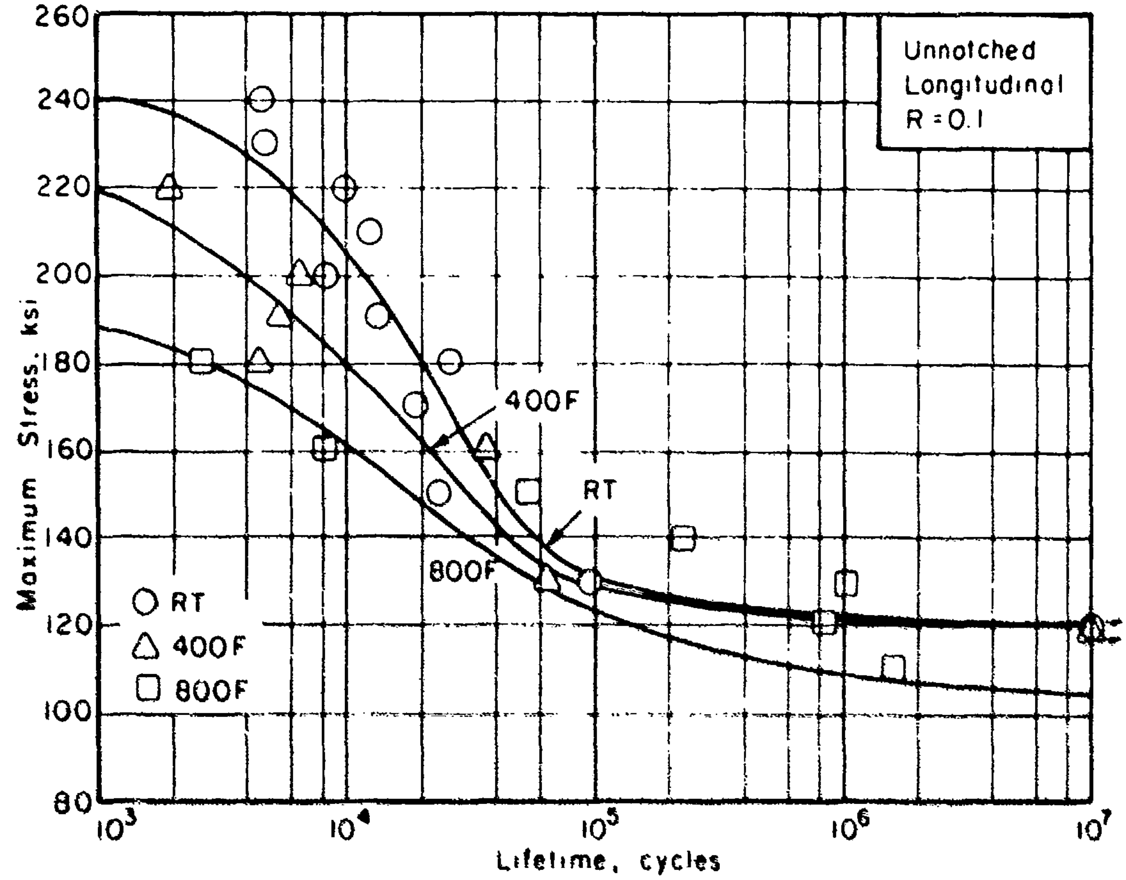

FIGURE 71. AXIAL-LOAD FATIGUE RESULTS FOR UNNOTCHED CUSTOM 455 ROUND BAR

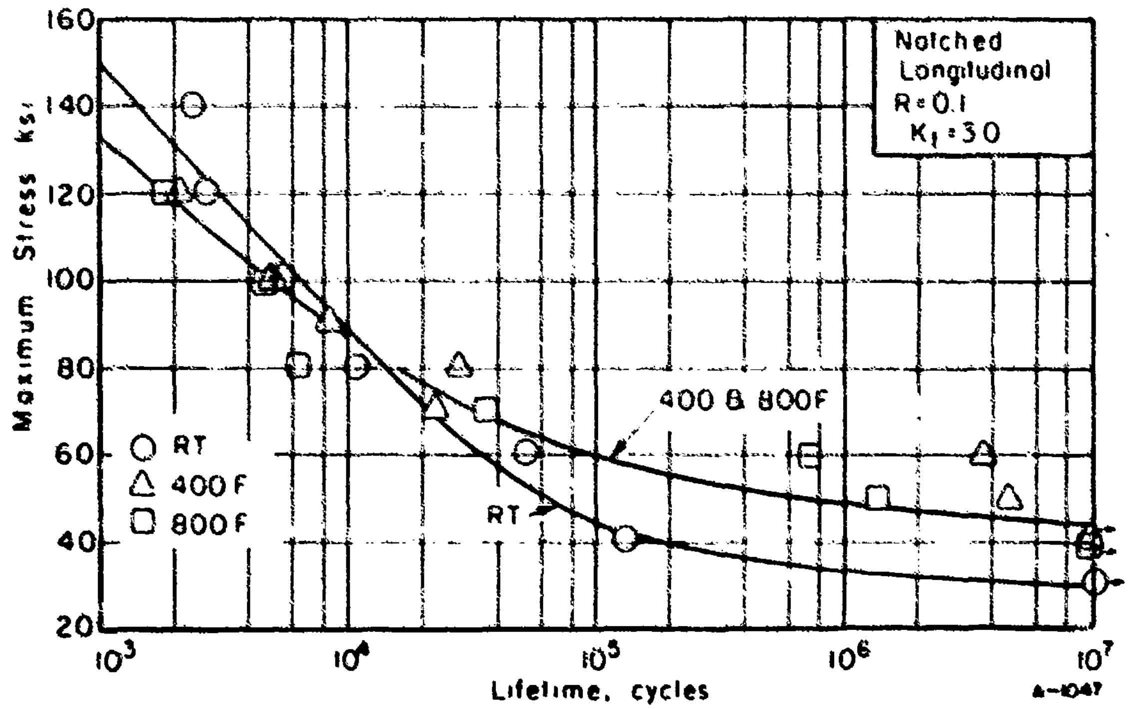

FIGURE 72. AXIAL-LOAD FATIGUE RESULTS FOR NOTCHED (K_t = 3.0) CUSTOM 455 ROUND BAR

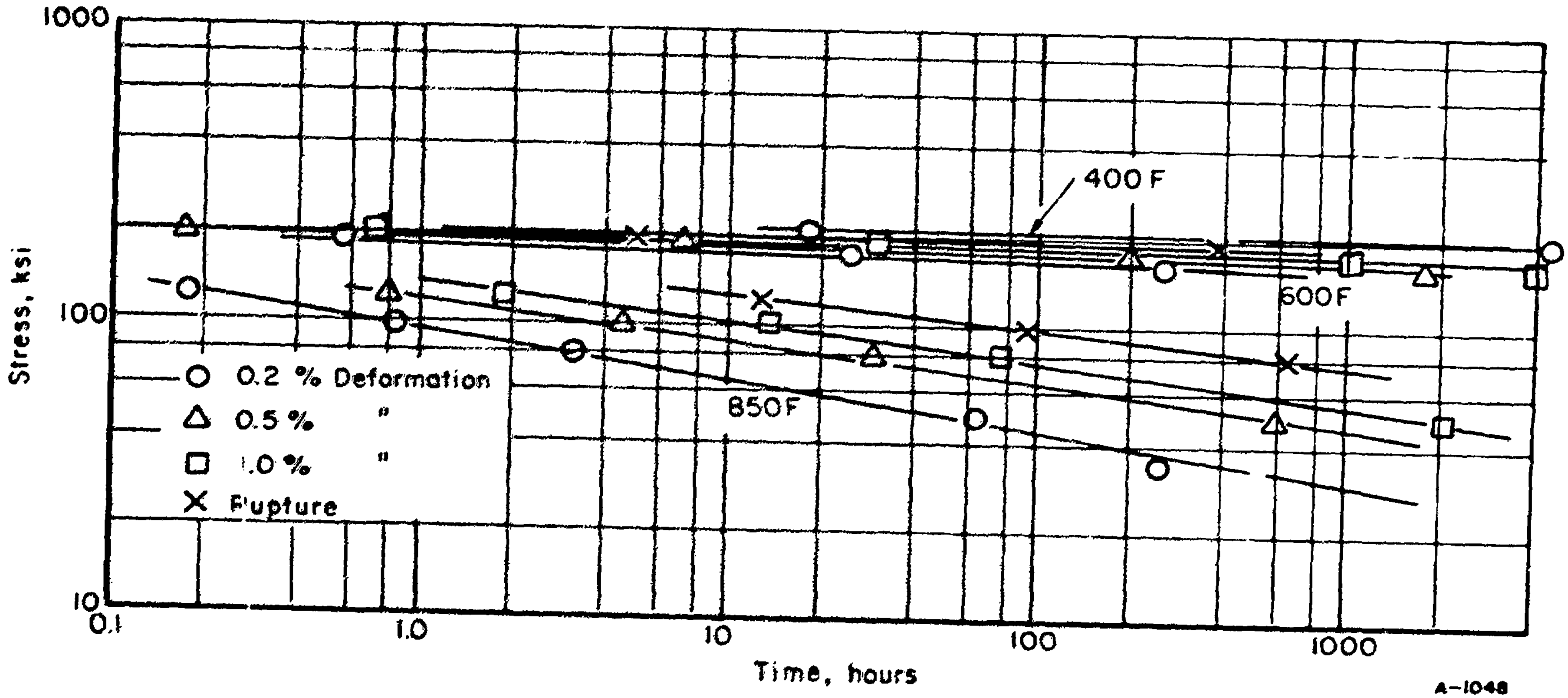

FIGURE 73. STRESS-RUPTURE AND PLASTIC DEFORMATION CURVES FOR CUSTOM 455 ROUND BAR

PH 14-8 Mo Stainless Steel

Material Description

PH 14-8 Mo is a recent addition to the Armco Steel Company's family of precipitation hardenable stainless steels. It is a semi-austenitic alloy developed to provide a sheet and strip product with higher resistance to crack propagation than the older 17-7 PH and PH 15-7 Mo alloys. It is heat treatable to high strengths and exhibits good elevated temperature properties. Since it is austenitic in the anneald condition, it is readily formable by methods currently used for austenitic or other semiaustenitic stainless steels. The alloy does work harden rapidly and may require intermediate anneals for deep drawn or other severely formed parts.

PH 14-8 Mo is available in the form of sheet and strip.

One sheet of 0.070-inch by 36-inch x 120-inch material from Heat V6448 was purchased from Armco for this evaluation.

The composition of this material was as follows:

Chemical Composition	Percent
Carbon	0.038
Manganese	0.10
Phosphorus	0.003
Sulfur	0.004
Silicon	0.10
Chromium	14.95
Nickel	8.31
Molybdenum	2.15
Aluminum	1.17
	Balance

Processing and Heat Treating

The specimen layout is shown in Figure 74. The sheet was received in the annealed condition (Condition A). After machining, the specimens were heat-treated to Condition SRH 1050 as recommended by Armco. This involves heating to 1700F, holding for 1 hour, air cool to 75F and within 1 hour cool to -100F, hold at -100F for 8 hours, heat to 1050F, hold for 1 hour, and air cool.

Test Results

Tension. Tests were performed at room temperature, 400F, 700F, and 900F in both the longitudinal and transverse directions. Tabular test results are presented in Table XXXVIII. Stress-strain curves at temperature are shown in Figures 75 and 76 . Effect-of-temperature curves are presented in Figure 79.

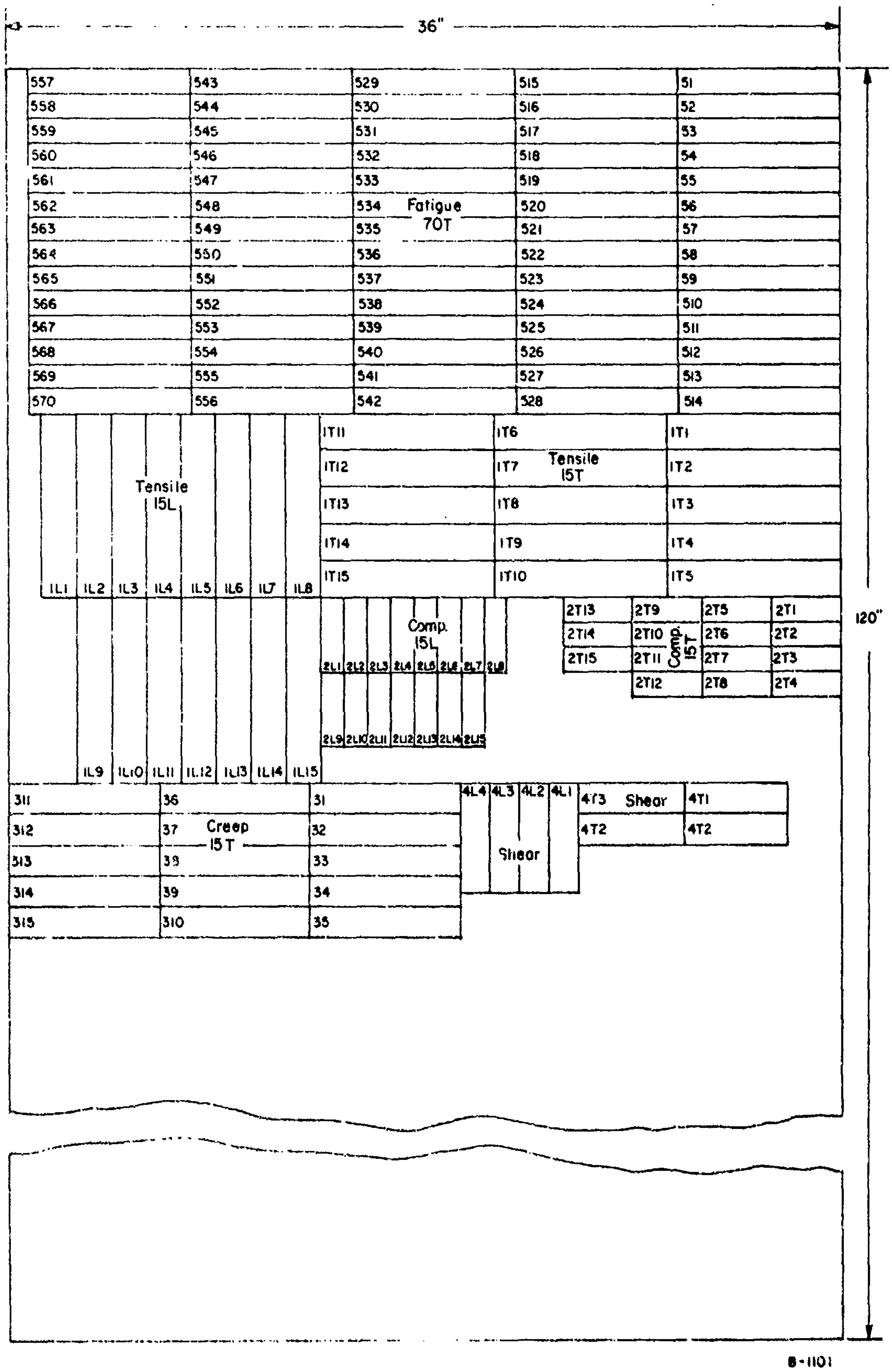

FIGURE 74. SPECIMEN LAYOUT FOR PH 14-8Mo SHEET

Compression. These tests were also conducted at room temperature, 400F, 700F, and 900F for both the longitudinal and transverse directions. Results are given in tabular form in Table XXXIX. Stress-strain and tangent modulus curves at temperature are presented in Figures 77 and 78. Effect-of-temperature curves are presented in Figure 80.

Shear. Results of shear tests in the longitudinal and transverse directions at room temperature are given in Table XL.

Fracture Toughness. Tests were conducted on specimens of full sheet thickness x 18 inches x 48 inches. The average K_c obtained was 270 ksi$\sqrt{\text{inch}}$. This number is considered valid.

Fatigue. Axial-load tests were conducted for unnotched and notched transverse specimens at room temperature, 400F, and 700F. Tabular results are given in Tables XLI and XLII. S-N curves are presented in Figures 81 and 82.

Creep and Stress-Rupture. Tests on transverse specimens were conducted at 700F, 900F, and 1100F. Tabular test results are given in Table XLIII. Log-stress versus log-time curves are presented in Figure 83.

Stress Corrosion. No cracks appeared in the specimens after testing as described in the experimental procedure section of this report.

Thermal Expansion. Values are given in the data sheet in the conclusions section of this report.

Density. Values are given in the data sheet in the conclusions section of this report.

TABLE XXXVIII. TENSION TEST RESULTS FOR PH 14-8 Mo SHEET

Specimen Number	Ultimate Tensile Strength, ksi	0.2 Percent Offset Yield Strength, ksi	Elongation in 2 inches, percent	Tensile modulus psi x 10^6
		Longitudinal at Room Temperature		
1L1	205.0	201.0	7.0	26.4
1L2	203.0	200.0	7.0	27.8
1L3	202.0	197.0	8.5	27.3
		Transverse at Room Temperature		
1T1	207.0	202.0	7.0	28.6
1T2	207.0	201.0	7.0	29.4
1T3	208.0	202.0	7.5	27.8
		Longitudinal at 400F		
1L4	183.0	175.0	6.0	26.3
1L5	182.0	173.0	6.0	25.3
1L6	182.0	173.0	6.0	26.4
		Transverse at 400F		
1T4	186.0	178.0	5.0	28.0
1T5	186.0	177.0	5.5	28.8
1T6	185.0	176.0	5.5	28.4
		Longitudinal at 700F		
1L7	164.0	151.0	10.0	26.4
1L8	163.0	151.0	9.5	25.2
1L9	166.0	154.0	9.5	25.1
		Transverse at 700F		
1T7	168.0	157.0	7.5	25.0
1T8	168.0	157.0	9.0	26.3
1T9	167.0	155.0	8.5	27.1
		Longitudinal at 900F		
1L10	132.0	120.0	17.5	23.1
1L11	130.0	121.0	18.5	22.8
1L12	131.0	119.0	18.5	23.5
		Transverse at 900F		
1T10	134.0	125.0	16.0	24.1
1T11	134.0	124.0	16.0	24.0
1T12	134.0	122.0	15.0	22.3

TABLE XXXIX. COMPRESSION TEST RESULTS FOR PH 14-8 Mo SHEET

Specimen Number	0.2 Percent Offset Yield Strength, ksi	Compressive Modulus, psi x 10^6
	Longitudinal at Room Temperature	
2L1	219.0	27.4
2L2	218.0	27.6
2L3	218.0	27.8
	Transverse at Room Temperature	
2T1	220.0	30.7
2T2	218.0	30.6
2T3	219.0	30.2
	Longitudinal at 400F	
2L4	198.0	25.0
2L5	197.0	25.7
2L6	198.0	25.8
	Transverse at 400F	
2T4	205.0	26.8
2T5	201.0	27.4
2T6	203.0	27.0
	Longitudinal at 700F	
2L7	177.0	25.8
2L8	176.0	25.0
2L9	176.0	24.7
	Transverse at 700F	
2T7	181.0	26.3
2T8	179.0	26.2
2T9	182.0	26.4
	Longitudinal at 900F	
2L10	137.0	24.6
2L11	138.0	24.5
2L12	138.0	24.1
	Transverse at 900F	
2T10	146.0	25.5
2T11	147.0	25.5
2T12	147.0	26.1

TABLE XL. SHEAR TEST RESULTS FOR PH 14-8 Mo SHEET AT ROOM TEMPERATURE

Specimen Number	Ultimate Shear Strength, ksi
Longitudinal	
4L1	130.0
4L2	130.0
4L3	130.0
4L4	131.0
Transverse	
4T1	129.0
4T2	129.0
4T3	128.0
4T4	129.0

TABLE XLI. AXIAL LOAD FATIGUE TEST RESULTS FOR UNNOTCHED PH 14-8 Mo SHEET AT A STRESS RATIO OF R=0.1

Specimen Number	Maximum Stress, ksi	Lifetime, Cycles
	Room Temperature	
51	190.0	1,072
52	170.0	12,000
53	170.0	11,200
54	150.0	21,500
55	130.0	33,000
56	110.0	80,800
57	100.0	121,200
58	90.0	10,000,000(a)
	400F	
59	190.0	125
510	170.0	8,100
511	150.0	14,600
512	130.0	28,600
513	110.0	183,000
514	100.0	44,400
515	90.0	126,300
516	80.0	11,765,900(a)
	700F	
518	190.0	300
519	170.0	1,100
520	150.0	6,700
522	130.0	17,400
523	110.0	35,100
524	100.0	47,100
525	90.0	73,700
526	80.0	6,446,000

(a) Did Not Fail

TABLE XLII. AXIAL LOAD FATIGUE TEST RESULTS FOR NOTCHED (K_t = 3.0) PH 14-8 Mo SHEET AT A STRESS RATIO OF R = 0.1

Specimen Number	Maximum Stress, ksi	Lifetime, Cycles
	Room Temperature	
528	100.0	9,200
529	90.0	8,700
530	70.0	21,400
531	50.0	36,400
532	40.0	131,200
533	30.0	16,771,300[a]
	400 F	
542	100.0	6,500
543	90.0	9,000
544	80.0	11,300
545	70.0	20,700
546	60.0	23,500
547	50.0	50,900
548	40.0	51,500
549	30.0	14,260,000[a]
	700 F	
535	100.0	4,000
536	90.0	4,900
538	70.0	8,720
539	60.0	18,800
540	50.0	29,700
541	40.0	11,698,000[a]

(a) Did not fail.

TABLE XLIII. SUMMARY DATA ON CREEP AND RUPTURE PROPERTIES OF PH14-8Mo SHEET

Specimen No.	Stress, ksi	Temp., F	Hours to Indicated Creep Deformation, percent					Initial Strain, percent	Rupture Time, hr	Elongation in 2 Inches, percent	Minimum Creep Rate, percent/hr
			0.1	0.2	0.5	1.0	2.0				
36	170	700	--	--	--	--	--	--	On Loading	3.6	--
[illegible]	160	700	0.03	0.05	0.13	0.3	0.83	1.324	2.7	9.3	1.6
39	[illegible]	700	0.15	0.7	3.7	20	135	0.546	1080.3[a]	5.57	0.0020
[illegible]	[illegible]	700	25	800	9300(est)	--	--	0.505	985.1[a]	0.718	0.000035
312	[illegible]	900	--	--	--	--	--	--	1.8	12.0	--
[illegible]	100	900	0.15	0.45	1.6	5	12	0.667	47.3	13.3	0.15
[illegible]	[illegible]	900	3	[illegible]	400	780	1300(est)	0.187	1195.9[a]	1.960	0.20383
[illegible]	[illegible]	900	[illegible]	2500(est)	6000(est)	--	--	0.024	616.2[a]	0.136	0.00006
[illegible]	[illegible]	1100	0.01	0.02	0.08	[illegible]	0.4	0.360	3.9	40.9	3.6
[illegible]	30	1100	[illegible]	0.2	0.5	1.3	3.9	0.131	103.5	29.7	0.11
[illegible]	20	1100	0.10	0.4	5.0	[illegible]	195	0.174	1101.2[a]	4.11	0.002
[illegible]	[illegible]	1100	[illegible]	[illegible]	650(est)	--	--	0.107	217.0[a]	0.467	0.00034
[illegible]	5.5	1100	980	2400(est)	6700(est)	--	--	0.162	909.3[a]	0.256	0.00007

(a) Test discontinued.

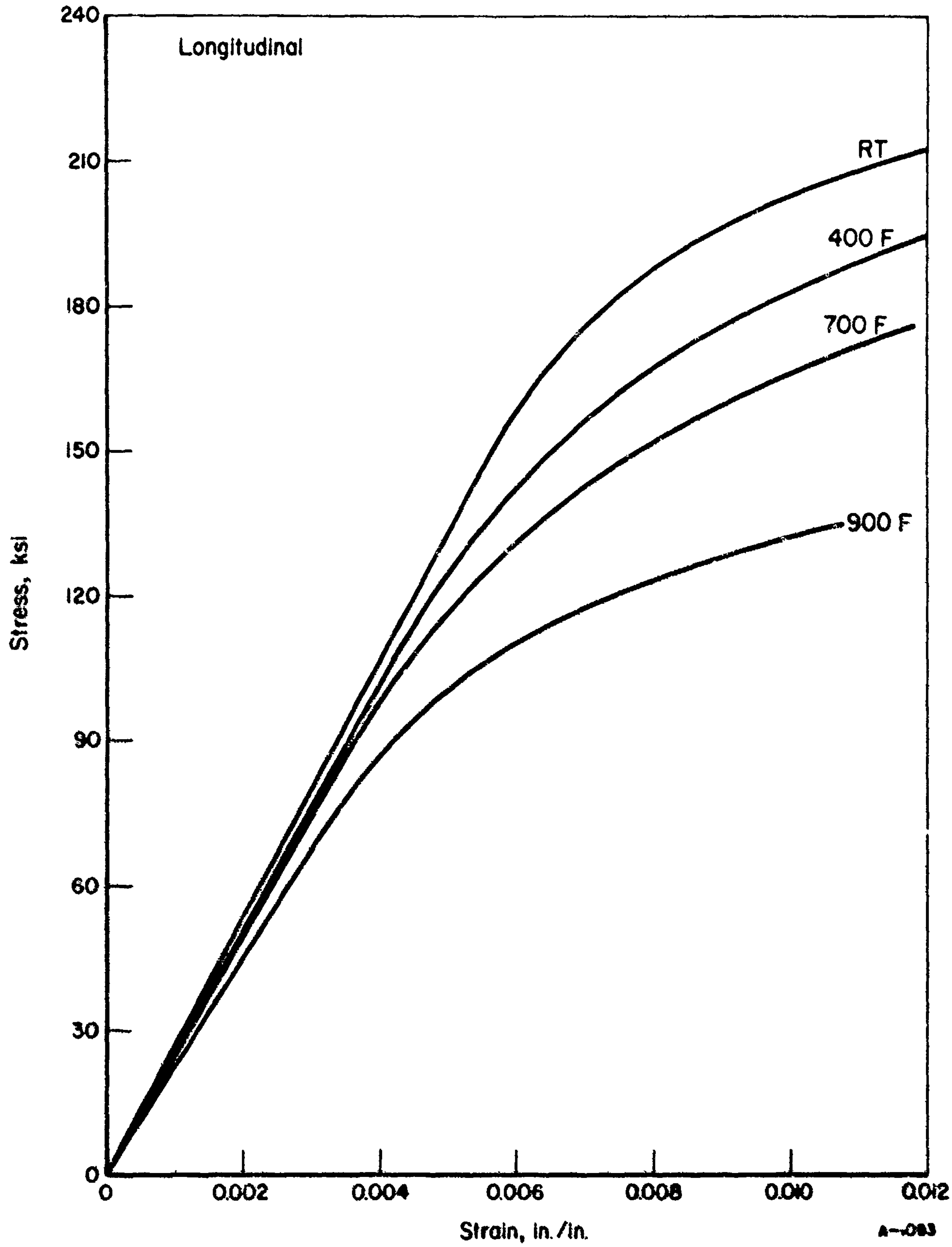

FIGURE 75. TYPICAL TENSILE STRESS-STRAIN CURVES FOR PH 14-8 Mo SHEET (LONGITUDINAL)

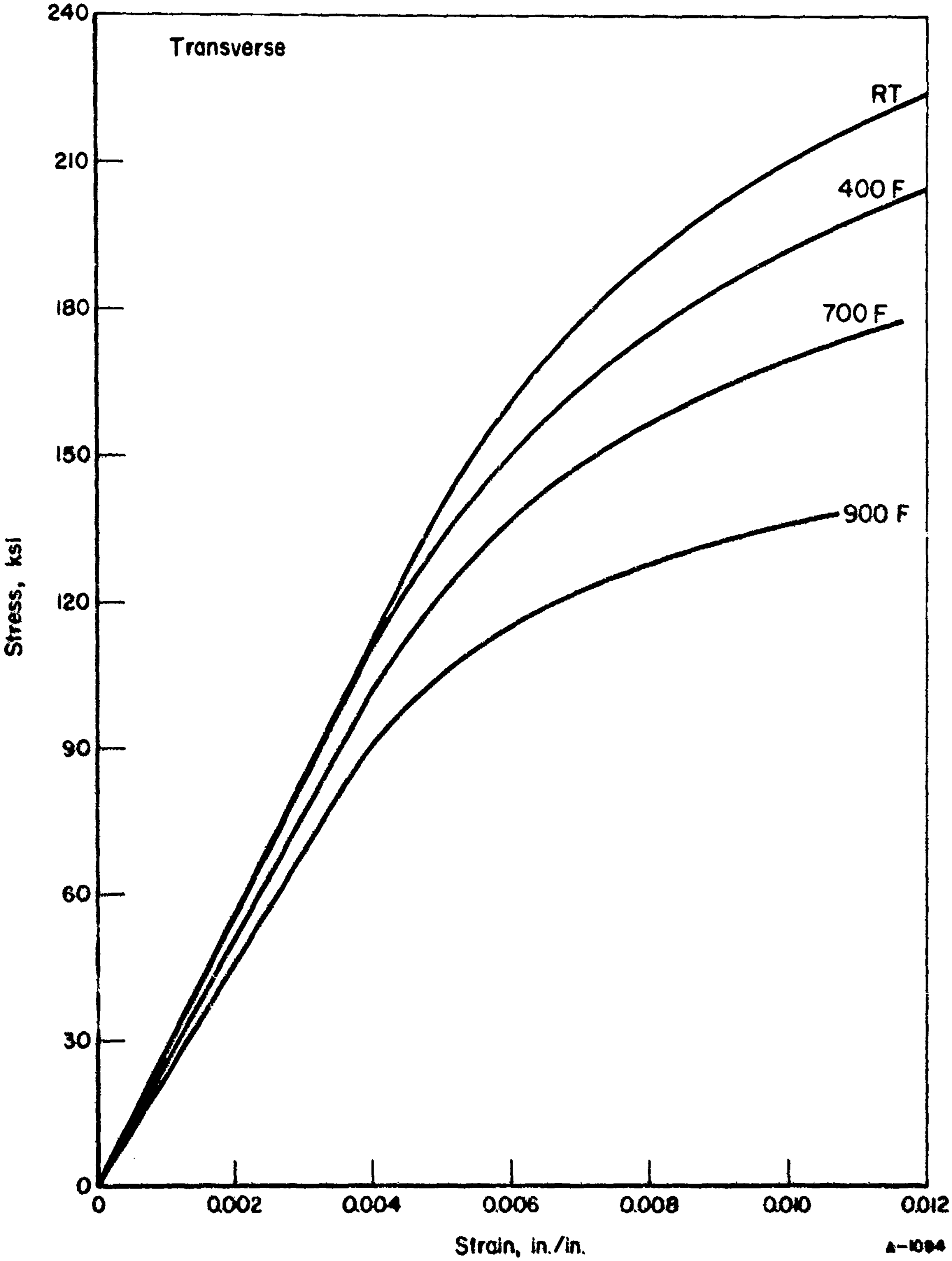

FIGURE 76. TYPICAL TENSILE STRESS-STRAIN CURVES FOR PH 14-8 Mo SHEET (TRANSVERSE)

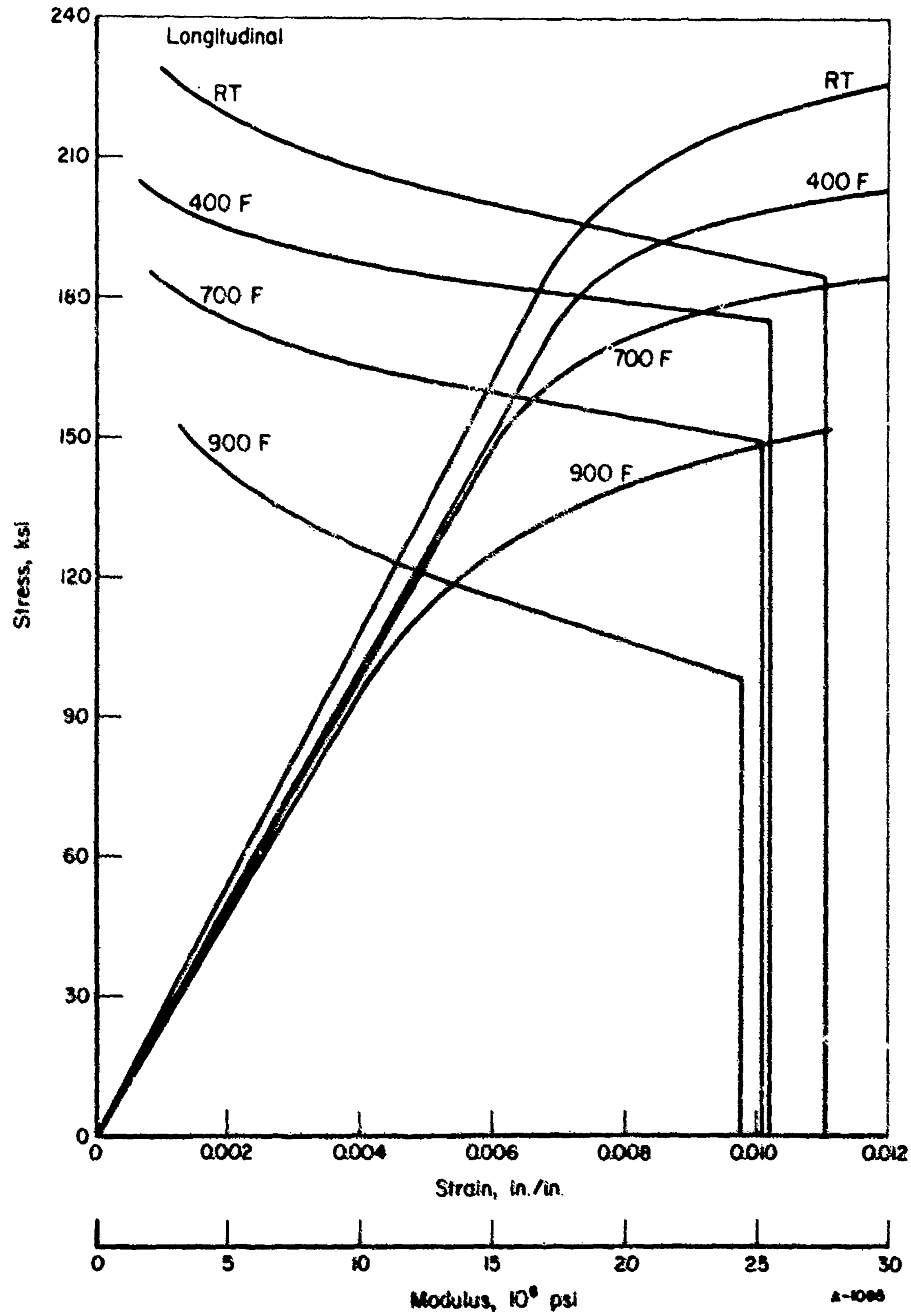

FIGURE 77. TYPICAL COMPRESSIVE STRESS-STRAIN AND TANGENT MODULUS CURVES FOR PH 14-8 Mo SHEET (LONGITUDINAL)

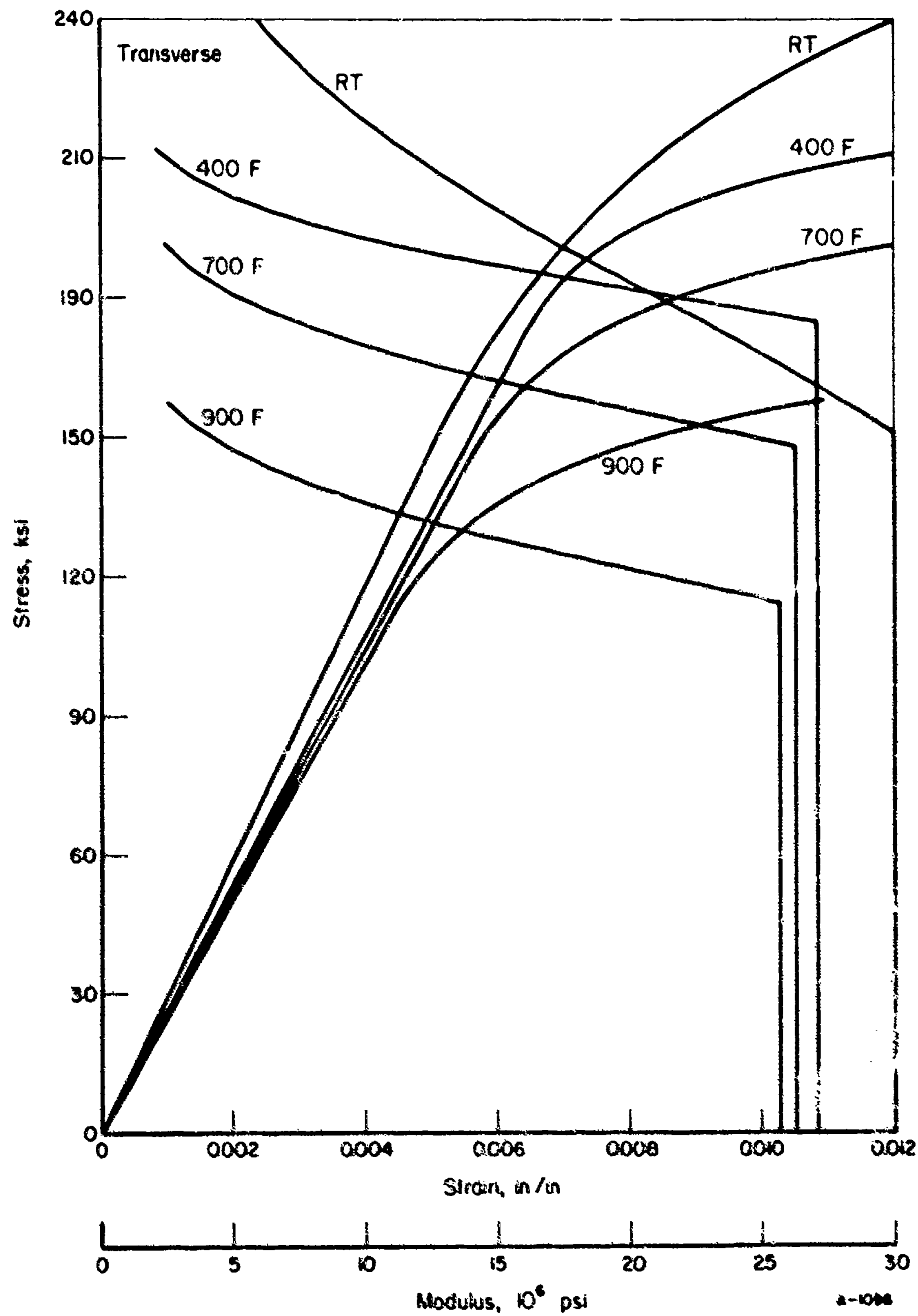

FIGURE 78. TYPICAL COMPRESSIVE STRESS-STRAIN AND TANGENT MODULUS CURVES FOR PH 14-8 Mo SHEET (TRANSVERSE)

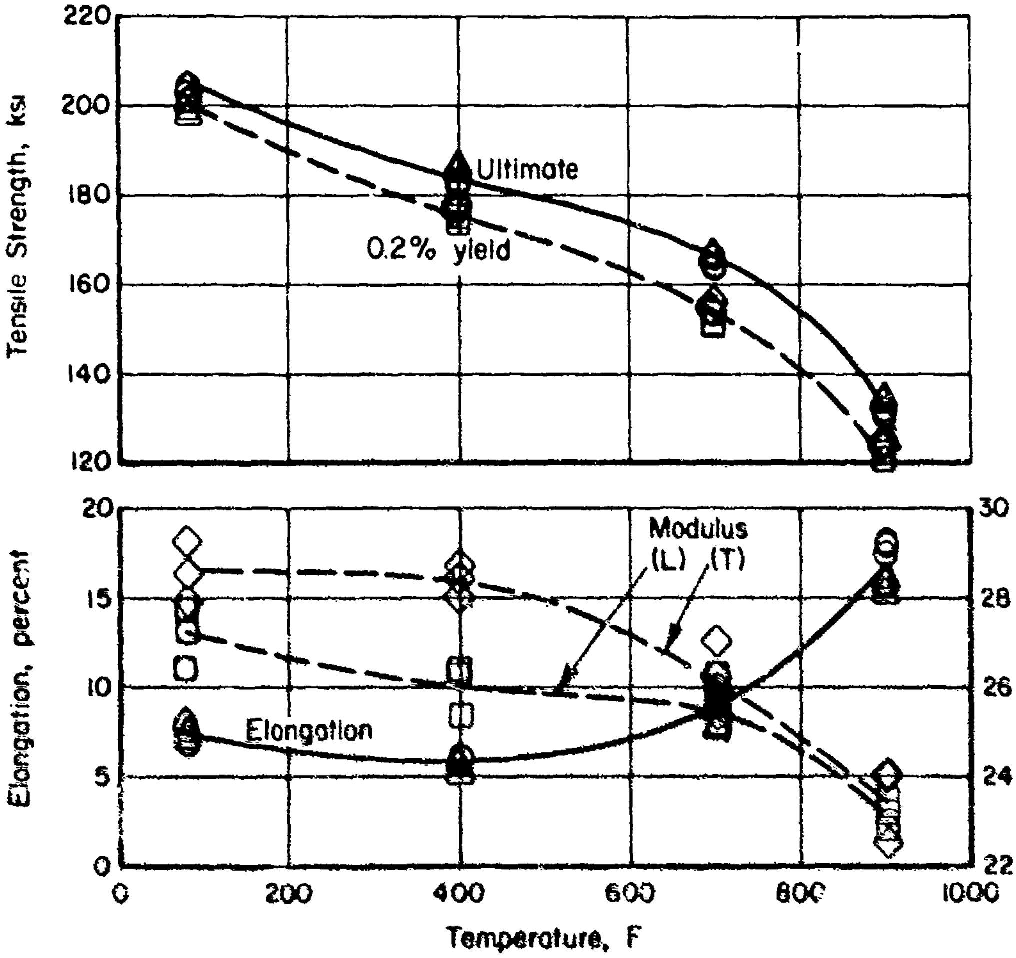

FIGURE 79. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF PH 14-8 Mo SHEET

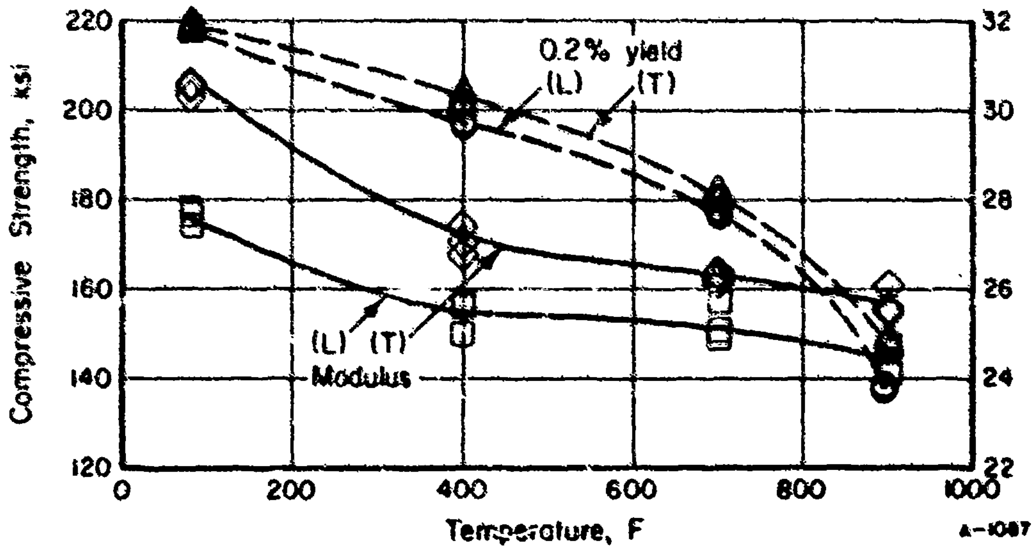

FIGURE 80. EFFECT OF TEMPERATURE ON THE COMPRESSIVE PROPERTIES OF PH 14-8 Mo SHEET

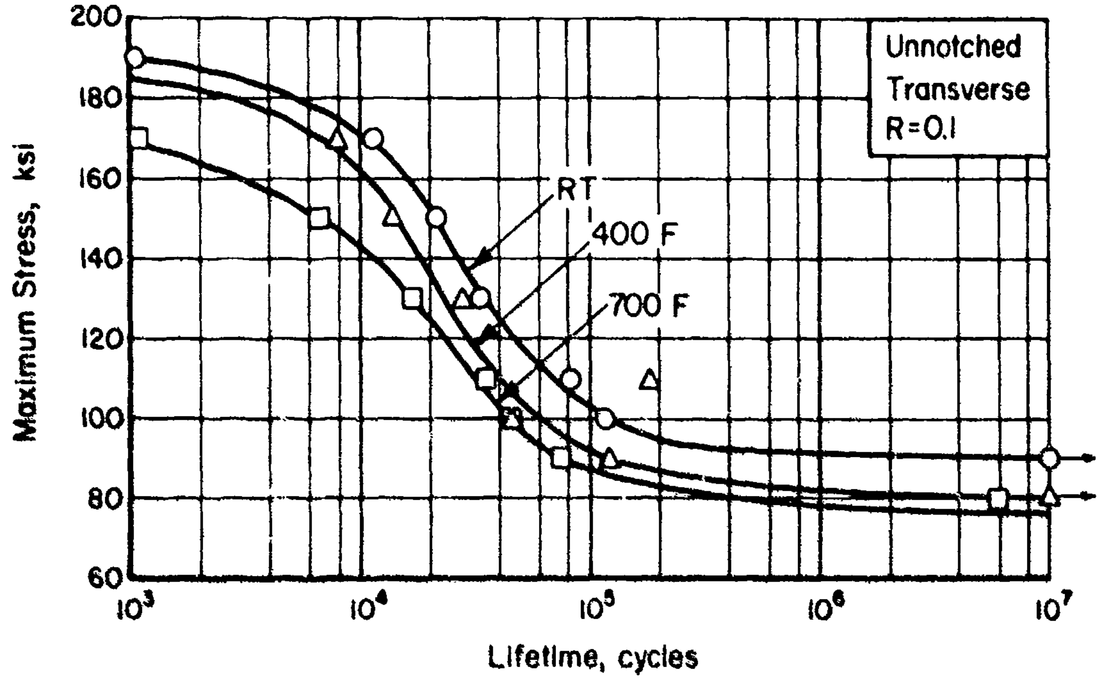

FIGURE 81. AXIAL LOAD FATIGUE RESULTS FOR PH 14-8Mo SHEET

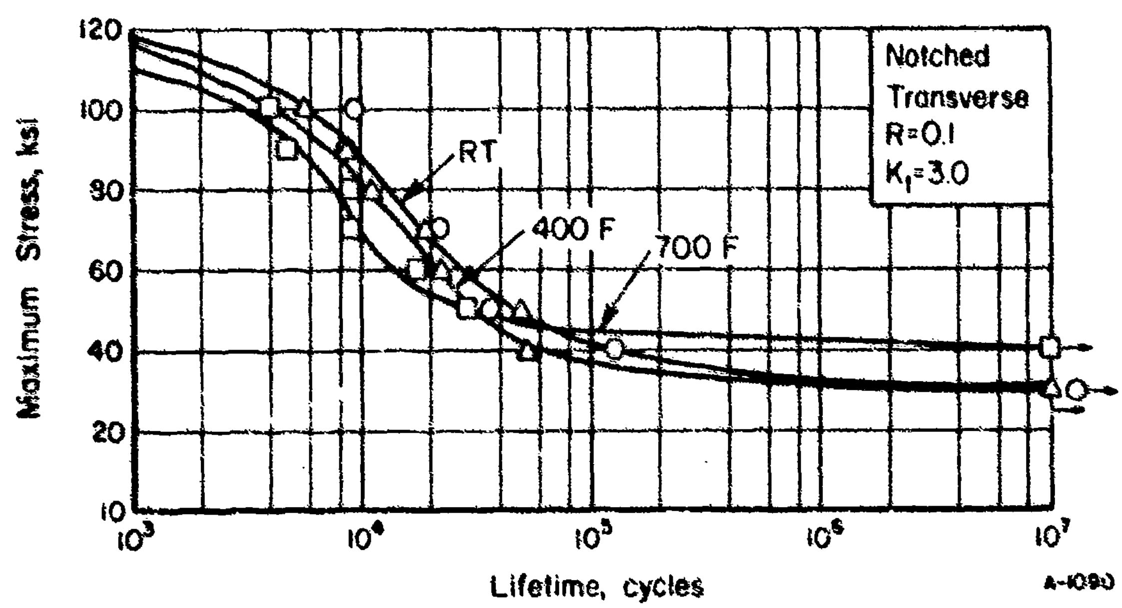

FIGURE 82. AXIAL LOAD FATIGUE RESULTS FOR NOTCHED (K_t=3.0) PH 14-8Mo SHEET

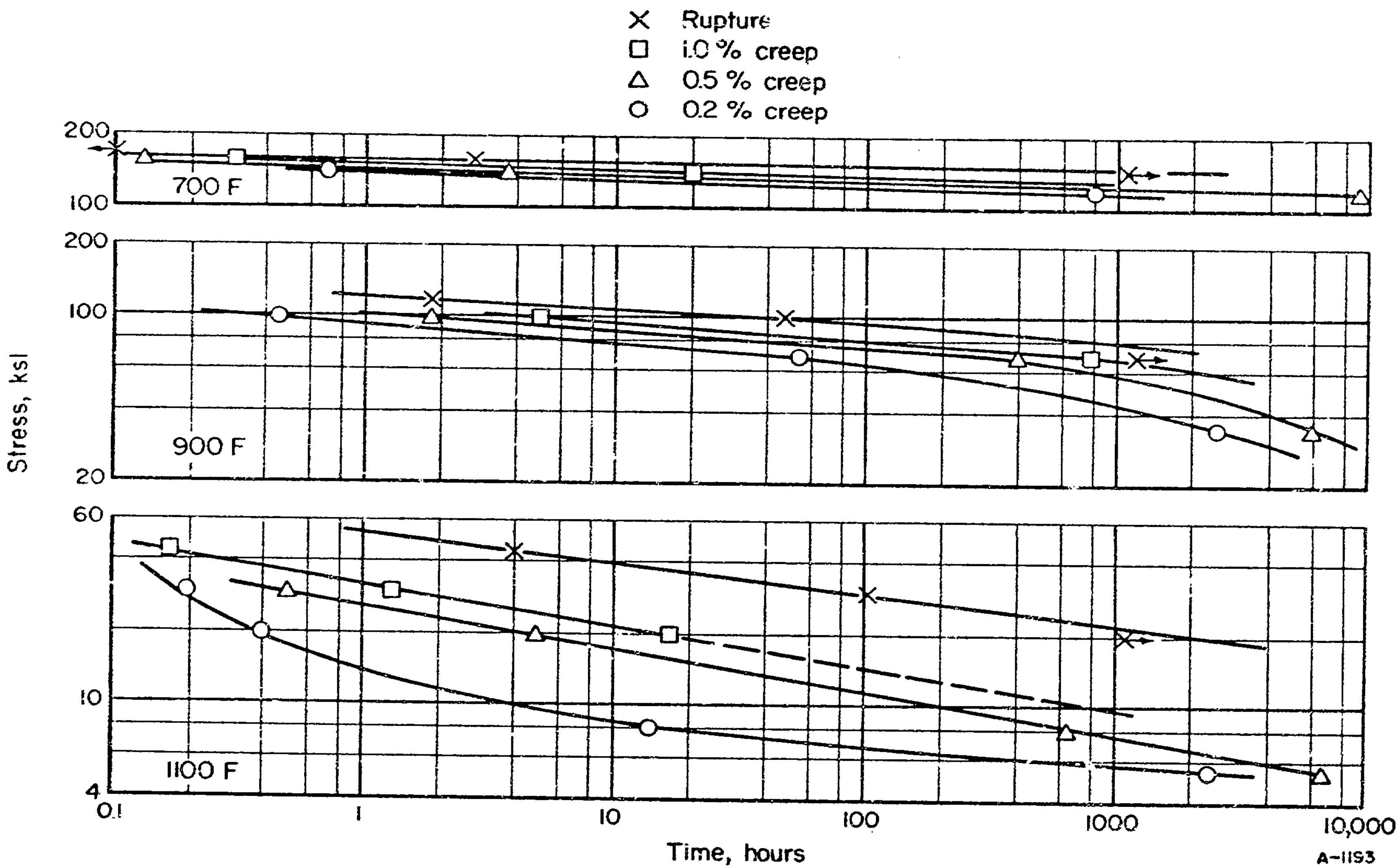

FIGURE 83. STRESS-RUPTURE AND PLASTIC DEFORMATION CURVES FOR PH 14-8 Mo STAINLESS STEEL SHEET

6Al-2Sn-4Zr-2Mo Titanium

Material Description

The 6-2-4-2 alloy was developed originally as one of the so-called "super" alpha alloys for engine usage, principally as forgings. However, it has also been produced in the form of flat-rolled products. These products are characterized by their high strength and stability at temperatures up to 1050 F.

Approximately 22 square feet of 0.080-inch-thick sheet was obtained from The Titanium Metals Corporation of America for this evaluation. The composition of the sheet was as follows:

Chemical Composition	Percent
Carbon	0.026
Iron	0.08
Nitrogen	0.008
Aluminum	5.8
Molybdenum	2.0
Hydrogen	0.007
Zirconium	4.2
Tin	2.1
Oxygen	0.10

Processing and Heat Treating

The specimen layout for this material is shown in Figure 84. After specimen machining, the alloy was triplex-annealed as follows: 1650 F for 1/2 hour, air cool; plus 1450 F for 1/4 hour, air cool; plus 1100 F for 2 hours and air cool. This treatment was recommended by The Titanium Metals Corporation of America.

Test Results

Tension. Testing was performed for both longitudinal and transverse specimens at room temperature, 400 F, 700 F, and 1000 F. Stress-strain curves at temperature are shown in Figures 85 and 86. Tabular test results are presented in Table XLIV. Effect-of-temperature curves are shown in Figure 89.

Compression. Testing was conducted for both longitudinal and transverse specimen at room temperature, 400 F, 700 F, and 1000 F. Tabular test results are given in Table XLV. Stress-strain and tangent-modulus curves at temperature are shown in Figures 87 and 88. Effect-of-temperature curves are presented in Figure 90.

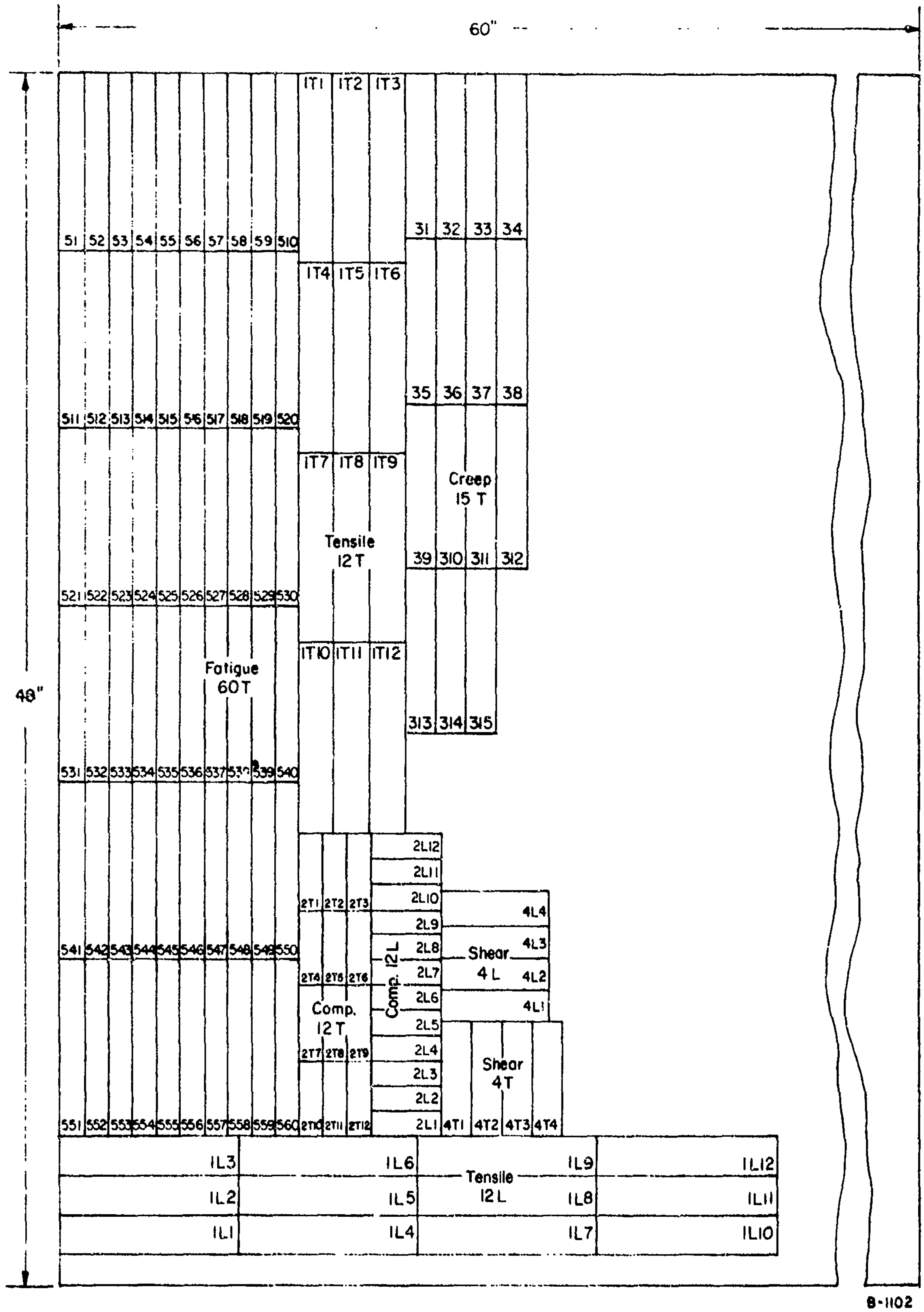

FIGURE 84. SPECIMEN LAYOUT FOR TI-6-2-4-2

Shear. Tests were performed at room temperature for longitudinal and transverse specimens. Results are given in Table XLVI.

Bend. Bend test results are given in the data sheet in the Conclusions section of this report.

Fracture Toughness. Tests were conducted on specimens of full-sheet thickness by 18 inches by 48 inches. The average K_c obtained was 135 ksi$\sqrt{\text{inch}}$. This number is considered valid.

Fatigue. Axial-load fatigue tests were conducted on unnotched and notched transverse specimens at room temperature, 400 F, and 700 F. Tabular test results are given in Tables XLVII and XLVIII. S-N curves are presented in Figures 91 and 92.

Creep and Stress Rupture. Tests were performed at 400 F, 700 F, and 1000 F on transverse specimens. Tabular test results are given in Table XLIX and log-stress versus log-time curves are presented in Figure 93.

Stress Corrosion. No cracks appeared in the specimens after testing as described in the Experimental Procedure section of this report.

Thermal Expansion and Density. Values obtained are given in the data sheet in the Conclusions section of this report.

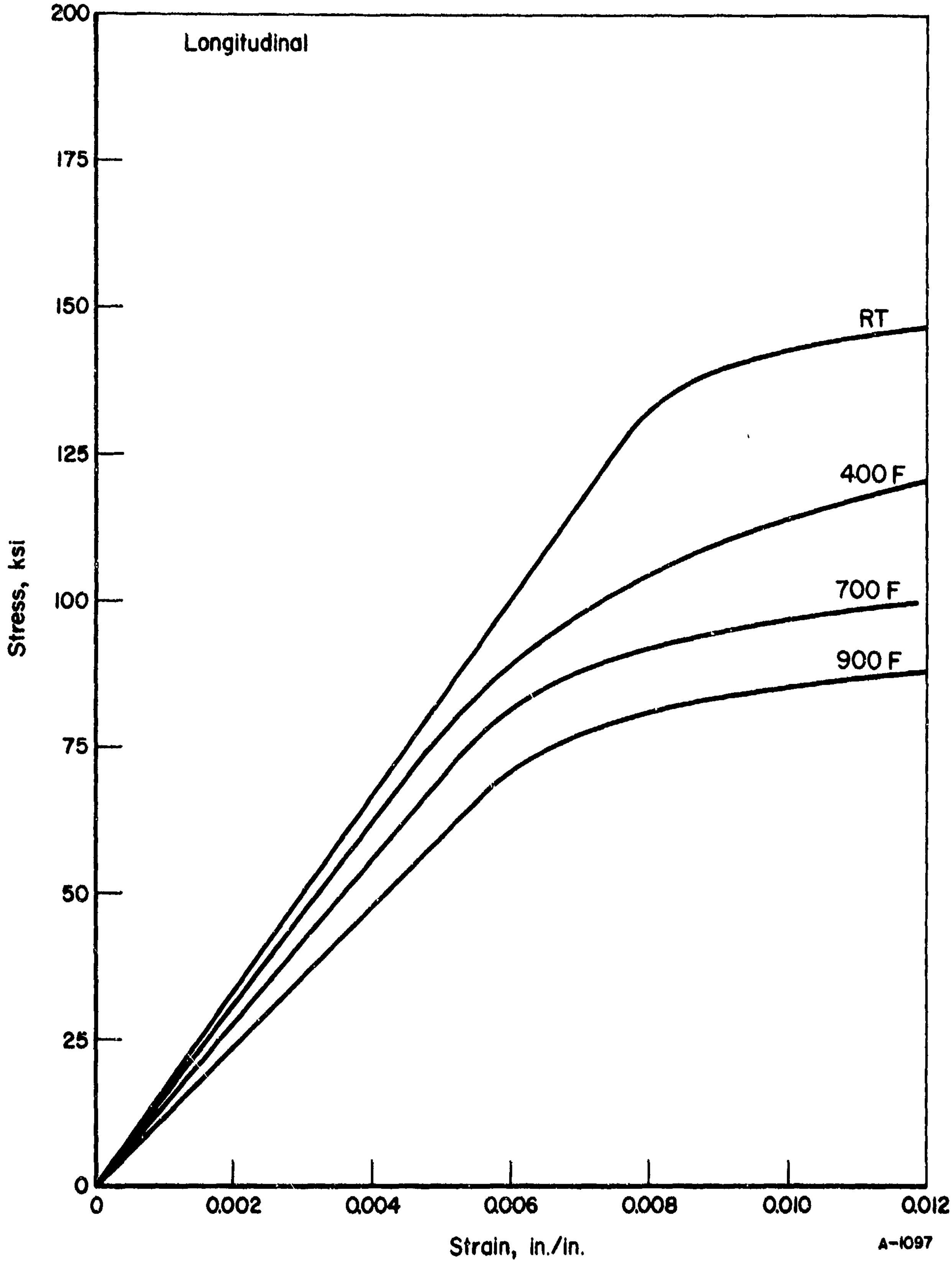

FIGURE 85. TYPICAL TENSILE STRESS-STRAIN CURVES FOR Ti-6Al-2Sn-4Zr-2Mo SHEET (LONGITUDINAL)

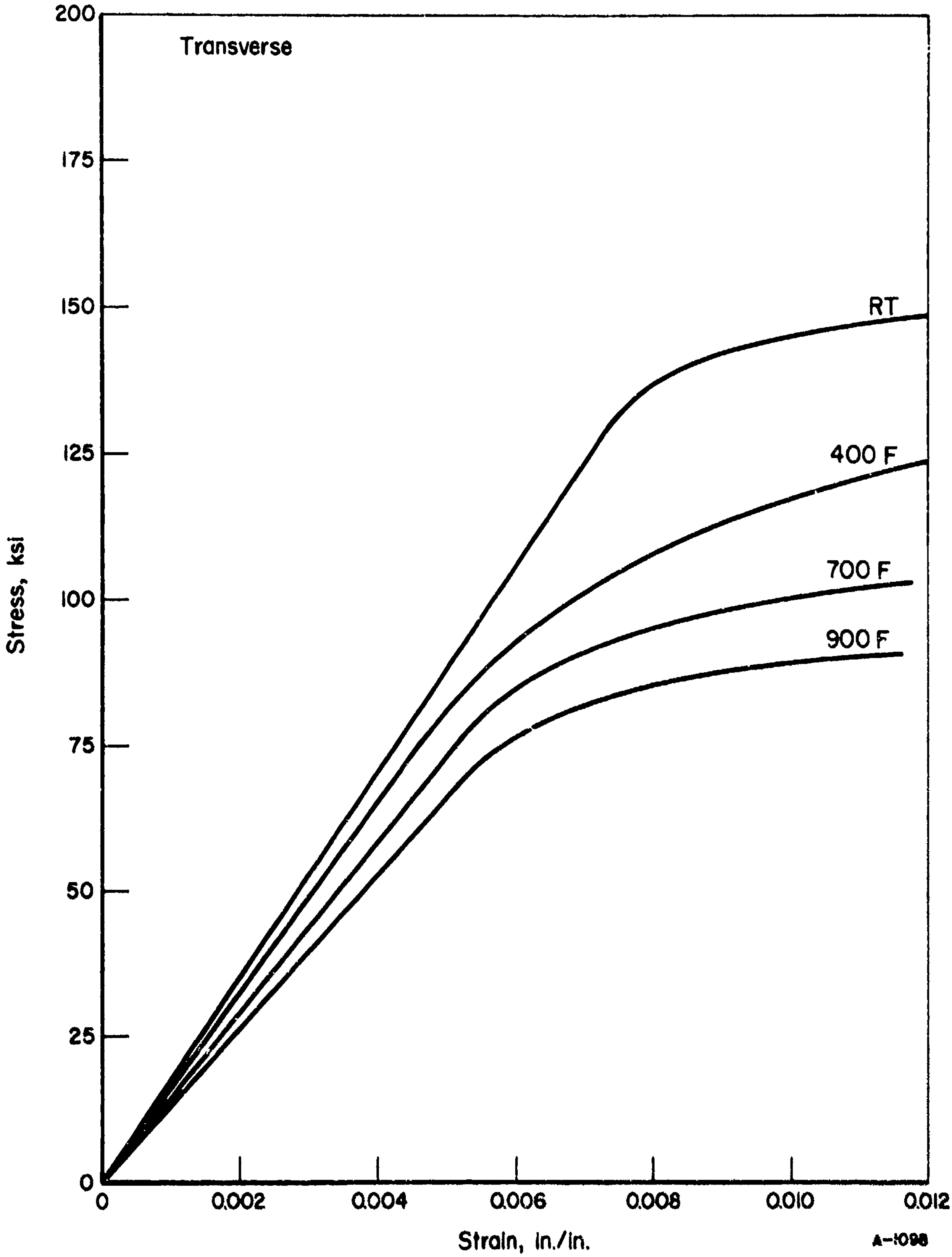

FIGURE 86. TYPICAL TENSILE STRESS-STRAIN CURVES FOR Ti-6Al-2Sn-4Zr-2Mo SHEET (TRANSVERSE)

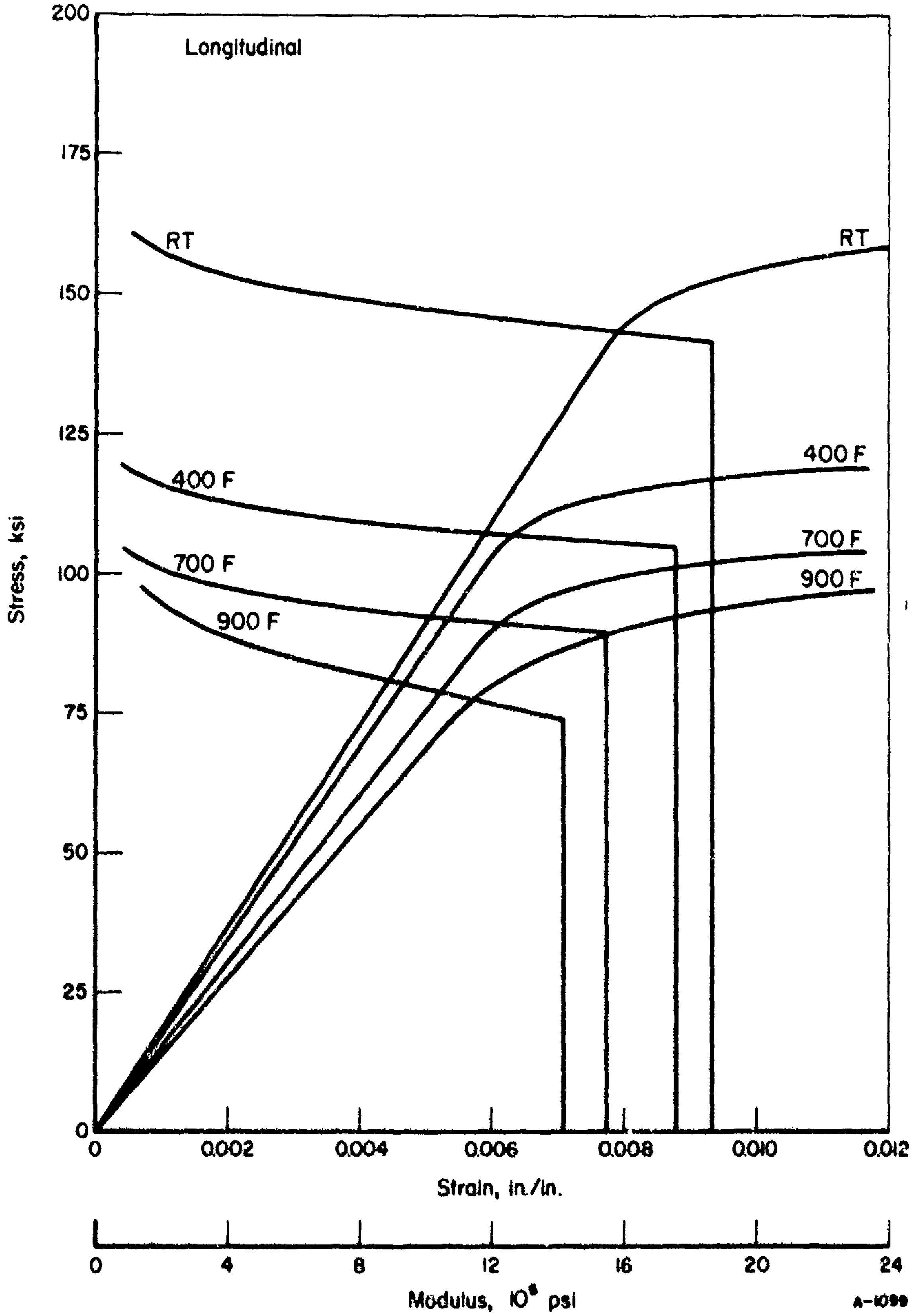

FIGURE 87. TYPICAL COMPRESSIVE STRESS-STRAIN AND TANGENT MODULUS CURVES FOR Ti-6Al-2Sn-4Zr-2Mo SHEET (LONGITUDINAL)

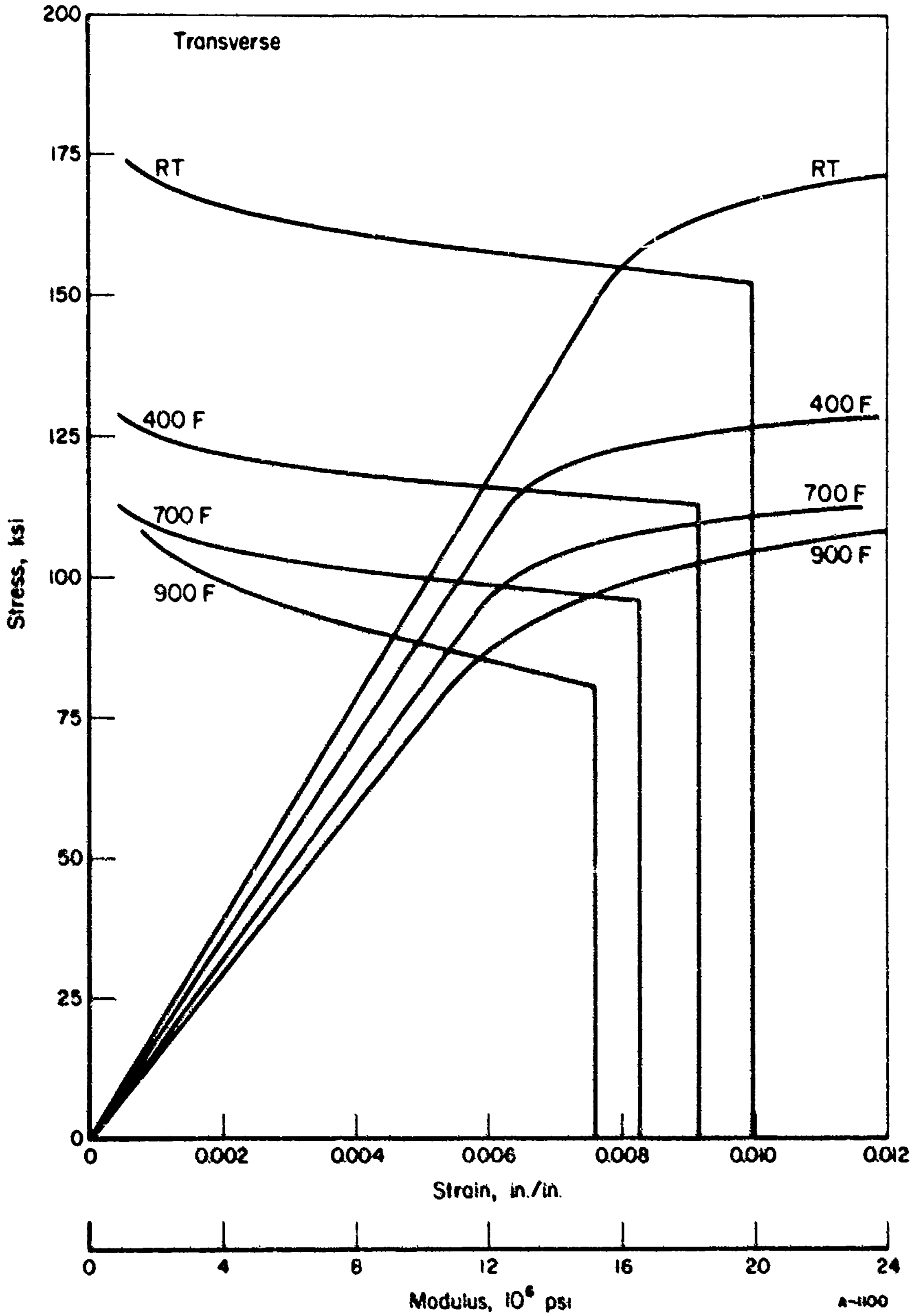

FIGURE 88. TYPICAL COMPRESSIVE STRESS-STRAIN AND TANGENT MODULUS CURVES FOR Ti-6Al-2Sn-4Zr-2Mo SHEET (TRANSVERSE)

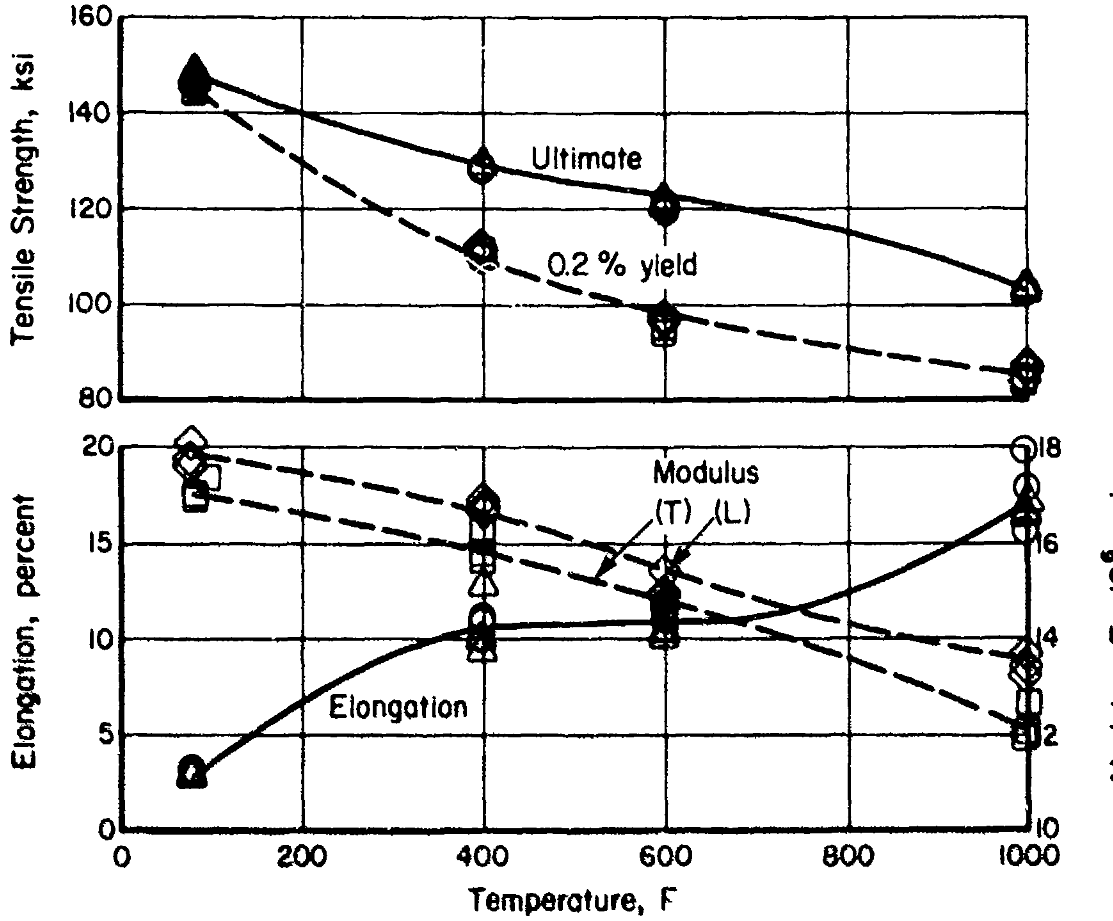

FIGURE 89. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF Ti-6Al-2Sn-4Zr-2Mo SHEET

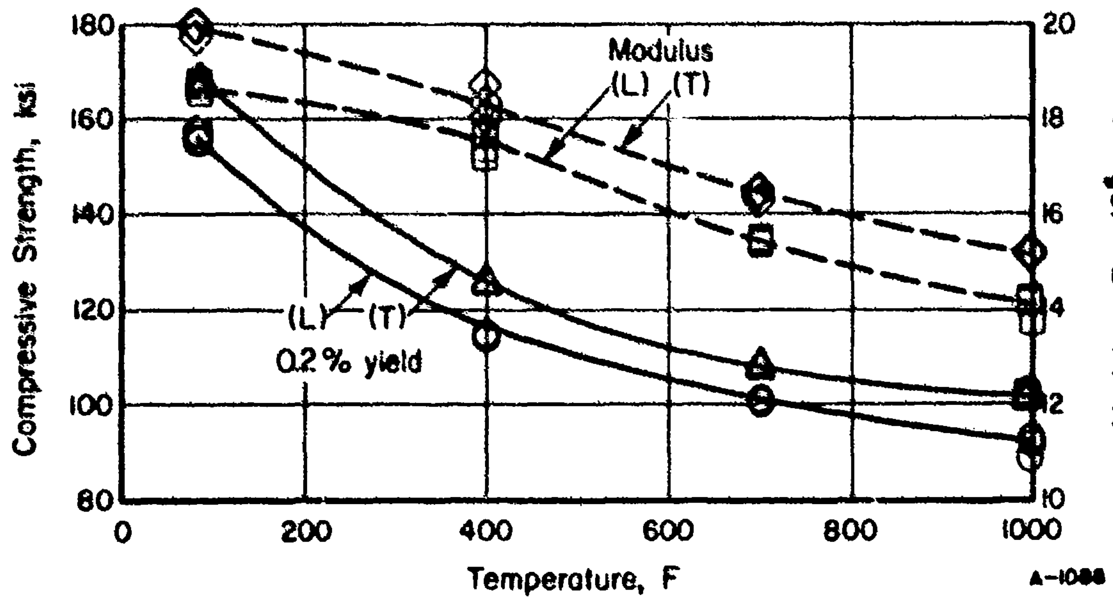

FIGURE 90. EFFECT OF TEMPERATURE ON THE COMPRESSIVE PROPERTIES OF Ti-6Al-2Sn-4Zr-2Mo SHEET

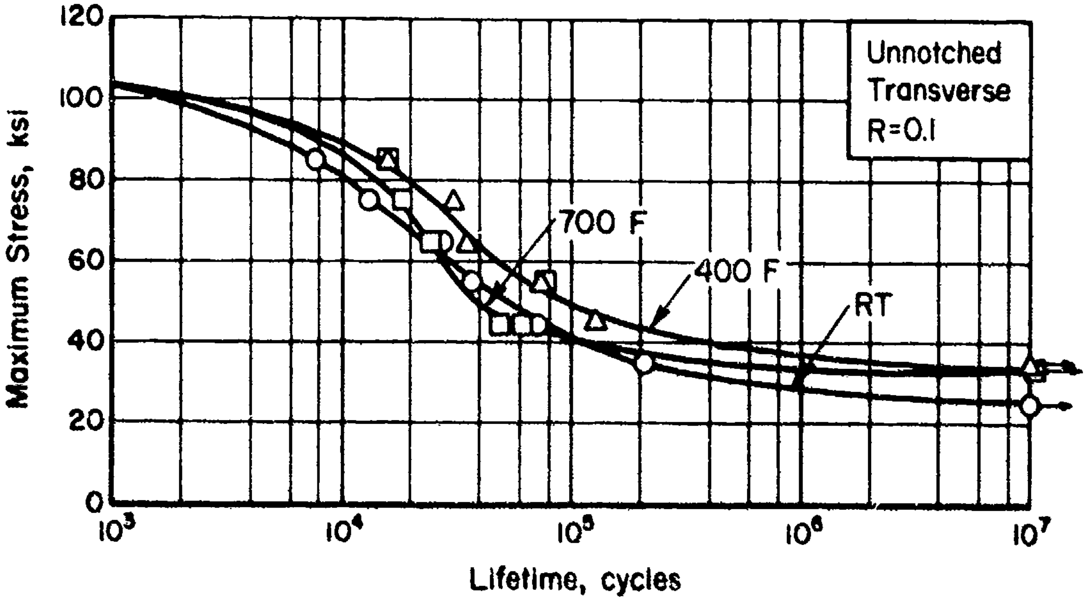

FIGURE 91. AXIAL LOAD FATIGUE RESULTS FOR Ti-6Al-2Sn-4Zr-2Mo SHEET

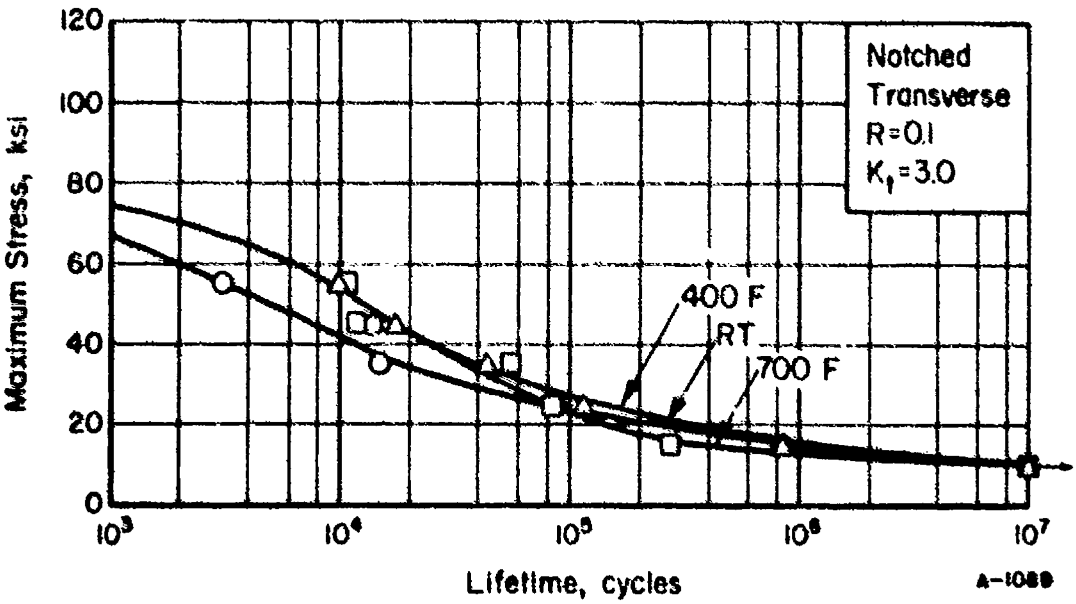

FIGURE 92. AXIAL LOAD FATIGUE RESULTS FOR NOTCHED (K_t=3.0) Ti-6Al-2Sn-4Zr-2Mo SHEET

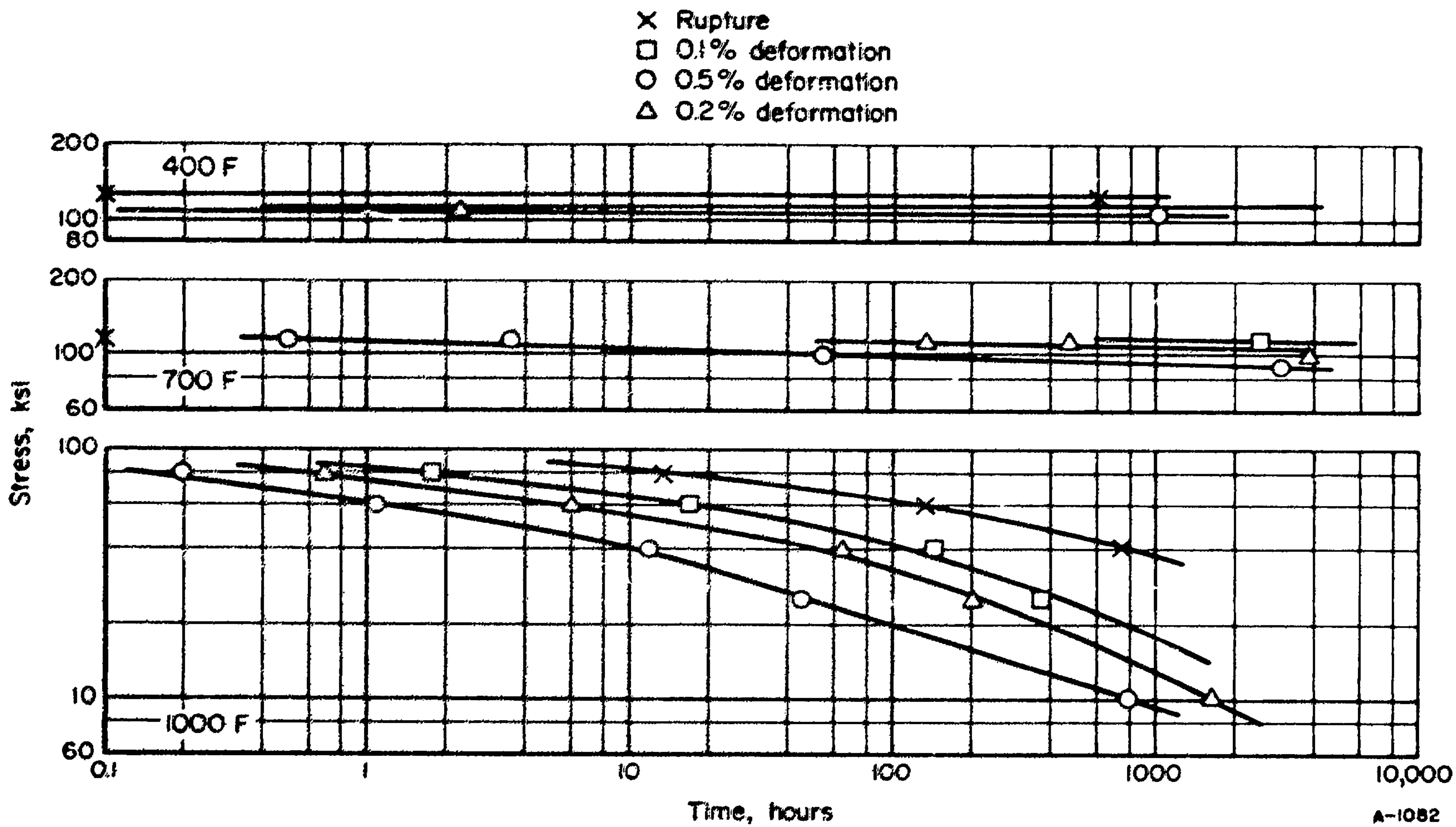

FIGURE 93. STRESS-RUPTURE AND PLASTIC DEFORMATION CURVES FOR Ti-6-2-4-2 SHEET

TABLE XLIV. TENSION TEST RESULTS FOR Ti-6Al-2Sn-4Zr-2Mo SHEET

Specimen Number	Ultimate Tensile Strength, ksi	0.2 Percent Offset Yield Strength, ksi	Elongation in 2 Inches, percent	Tensile Modulus, psi x 10^6
		Longitudinal at Room Temperature		
1L1	146.0	144.0	3.0	17.3
1L2	146.0	144.0	3.0	16.7
1L3	147.0	145.0	3.0	16.9
		Transverse at Room Temperature		
1T1	147.0	146.0	2.7	18.5
1T2	148.0	145.0	2.7	17.6
1T3	148.0	146.0	2.7	17.5
		Longitudinal at 400 F		
1L4	129.0	110.0	11.0	16.4
1L5	129.0	109.0	10.0	15.8
1L6	129.0	110.0	11.5	15.6
		Transverse at 400 F		
1T4	129.0	110.0	13.0	16.9
1T5	129.0	112.0	10.0	16.5
1T6	129.0	112.0	9.0	16.7
		Longitudinal at 700 F		
1L7	121.0	93.8	11.0	14.2
1L8	120.0	94.3	12.0	14.3
1L9	119.0	94.3	11.5	14.6
		Transverse at 700 F		
1T7	121.0	97.8	12.0	14.9
1T8	120.0	96.9	10.0	14.7
1T9	119.0	97.1	10.5	15.3
		Longitudinal at 1000 F		
1L10	103.0	83.6	15.5	12.6
1L11	103.0	83.6	18.0	12.1
1L12	102.0	83.1	20.0	11.9
		Transverse at 1000 F		
1T10	104.0	86.0	17.0	13.8
1T11	104.0	87.5	16.5	13.2
1T12	102.0	84.4	16.0	13.5

TABLE XLV. COMPRESSION TEST RESULTS FOR
Ti-6Al-2Sn-4Zr-2Mo SHEET

Specimen Number	0.2 Percent Offset Yield Strength, ksi	Compressive Modulus, psi x 10^6
	Longitudinal at Room Temperature	
2L1	155.0	18.6
2L2	156.0	18.5
2L3	158.0	18.7
	Transverse at Room Temperature	
2T1	168.0	19.7
2T2	169.0	20.0
2T3	169.0	19.9
	Longitudinal at 400 F	
2L4	116.0	17.7
2L5	116.0	17.2
2L6	116.0	17.5
	Transverse at 400 F	
2T4	125.0	18.8
2T5	125.0	18.2
2T6	125.0	18.0
	Longitudinal at 700 F	
2L7	101.0	15.5
2L8	101.0	15.5
2L9	101.0	15.3
	Transverse at 700 F	
2T7	109.0	16.3
2T8	108.0	16.5
2T9	109.0	16.6
	Longitudinal at 1000 F	
2L10	88.9	13.8
2L11	93.8	14.3
2L12	92.5	14.3
	Transverse at 1000 F	
2T10	102.0	15.2
2T11	100.0	15.2
2T12	101.0	15.2

TABLE XLVI. SHEAR TEST RESULTS FOR Ti-6Al-2Sn-4Zr-2Mo AT ROOM TEMPERATURE

Specimen Number	Ultimate Shear Strength, ksi
	Longitudinal
4L1	99.0
4L2	101.0
4L3	100.0
4L2	101.0
	Transverse
4T1	101.0
4T2	101.0
4T3	102.0
4T4	100.0

TABLE XLVII. AXIAL LOAD FATIGUE TEST RESULTS FOR UNNOTCHED Ti-6Al-2Sn-4Zr-2Mo SHEET AT A STRESS RATIO OF R = 0.1

Specimen Number	Maximum Stress, ksi	Lifetime, cycles
	Room Temperature	
51	85.0	7,900
52	75.0	13,500
53	65.0	27,000
55	55.0	36,400
56	45.0	70,100
57	35.0	202,400
58	25.0	10,000,000(a)
	400 F	
59	85.0	16,300
510	75.0	30,500
511	65.0	35,000
512	55.0	73,800
513	45.0	121,600
514	35.0	10,787,100(a)
	700 F	
515	85.0	17,600
516	75.0	18,600
517	65.0	25,100
518	55.0	78,200
519	45.0	49,000
520	45.0	61,400
521	35.0	12,742,000(a)

(a) Did not fail.

TABLE XLVIII. AXIAL LOAD FATIGUE TEST RESULTS FOR NOTCHED (K_t = 3.0) Ti-6Al-2Sn-4Zr-2Mo SHEET AT A STRESS RATIO OF R = 0.1

Specimen Number	Maximum Stress, ksi	Lifetime, cycles
	Room Temperature	
522	55.0	3,300
523	45.0	11,600
524	35.0	15,000
525	25.0	88,800
526	15.0	840,600
527	10.0	10,180,000[(a)]
	400 F	
528	55.0	10,400
529	45.0	18,800
530	35.0	43,000
531	25.0	109,900
532	15.0	826,700
533	10.0	11,069,300[(a)]
	700 F	
535	55.0	11,000
536	45.0	13,500
537	35.0	56,200
538	25.0	84,800
539	15.0	265,200
540	10.0	11,412,800[(a)]

(a) Did not fail.

TABLE XLIX. SUMMARY DATA ON CREEP AND RUPTURE PROPERTIES OF Ti-6-2-4-2 ALLOY SHEET

Specimen No.	Stress, ksi	Temp, F	Hours to Indicated Creep Deformation, percent					Initial Strain, percent	Rupture Time, hr	Elongation in 2 in., percent	Reduction of Area, percent	Minimum Creep Rate, percent/hr
			0.1	0.2	0.5	1.0	2.0					
Ti-6242-31	128.5	400	--	--	--	--	--	--	On loading	12.4	--	--
Ti-6242-34	124.0	"	--	--	0.03	0.15	--	5.315	600.3*	6.590	--	0.00002
Ti-6242-37	110.0	"	--	0.05	2.2	--	--	0.720	119.6*	1.262	--	--
Ti-6242-39	105	"	0.07	1000	--	--	--	0.669	1007.7*	0.876	--	0.00001
Ti-6242-314	120	700	--	--	--	--	--	--	On loading	11.5	--	--
Ti-6242-312	116	"	--	0.5	135	950	--	5.749	1126.9*	6.83	--	0.00040
Ti-6242-310	112	"	--	3.5	470	2500**	--	3.965	671.5*	4.53	--	0.00025
Ti-6242-32	100	"	0.05	55	3828**	--	--	1.152	665.1*	1.415	--	0.000075
Ti-6242-313	90	"	600	3000**	--	--	--	0.658	307*	0.780	--	0.00004
Ti-6242-35	80	1000	0.05	0.2	0.7	1.8	4.2	0.709	13.5	16.0	--	0.44
Ti-6242-33	60	"	0.35	1.1	6.0	17	45	0.558	133.8	24.9	--	0.031
Ti-6242-38	40	"	2.5	12	65	145	225	0.198	745.2	36.9	--	0.0075
Ti-6242-36	25	"	11	45	202	365	500**	0.453	289.4*	1.193	--	0.0019
Ti-6242-311	10	"	515	800	1625**	--	--	0.069	963.6*	0.327	--	0.00036

*Test discontinued.
**Estimate.

DISCUSSION OF PROGRAM RESULTS

As has been stated in previous reports issued on the Air Force "data sheet" program, the tendency in an evaluation program of this type is to compare the materials property information obtained with similar data on materials already in use. Whether such a comparison should be the deciding factor for interest in a newer alloy is open to question. Many criteria, such as forming characteristics, weldability, oxidation resistance, etc., can be of particular importance so that strength properties may become secondary. However, since first comparisons are usually made on the basis of mechanical strength (tensile ultimate and tensile yield) the data generated on this program are compared to information for similar alloys. Figures 94 and 95 are effect-of-temperature curves concerned with these properties.

CONCLUSIONS

The objective of this program was the generation of useful engineering data for newly developed structural materials. During the contract term the following materials were evaluated:

(1) Udimet 700 Alloy Sheet

(2) X5090 Alloy Sheet

(3) AF2-IDA Alloy Sheet

(4) Inconel 625 Alloy Sheet

(5) HA-188 Alloy Sheet

(6) Custom 455 Alloy Bar

(7) PH 14-8 Mo Alloy Sheet

(8) 6Al-2Sn-4Zr-2Mo Titanium Alloy Sheet.

A data sheet was issued for each material. As a summary, each of the data sheets is reproduced in this section of this final report.

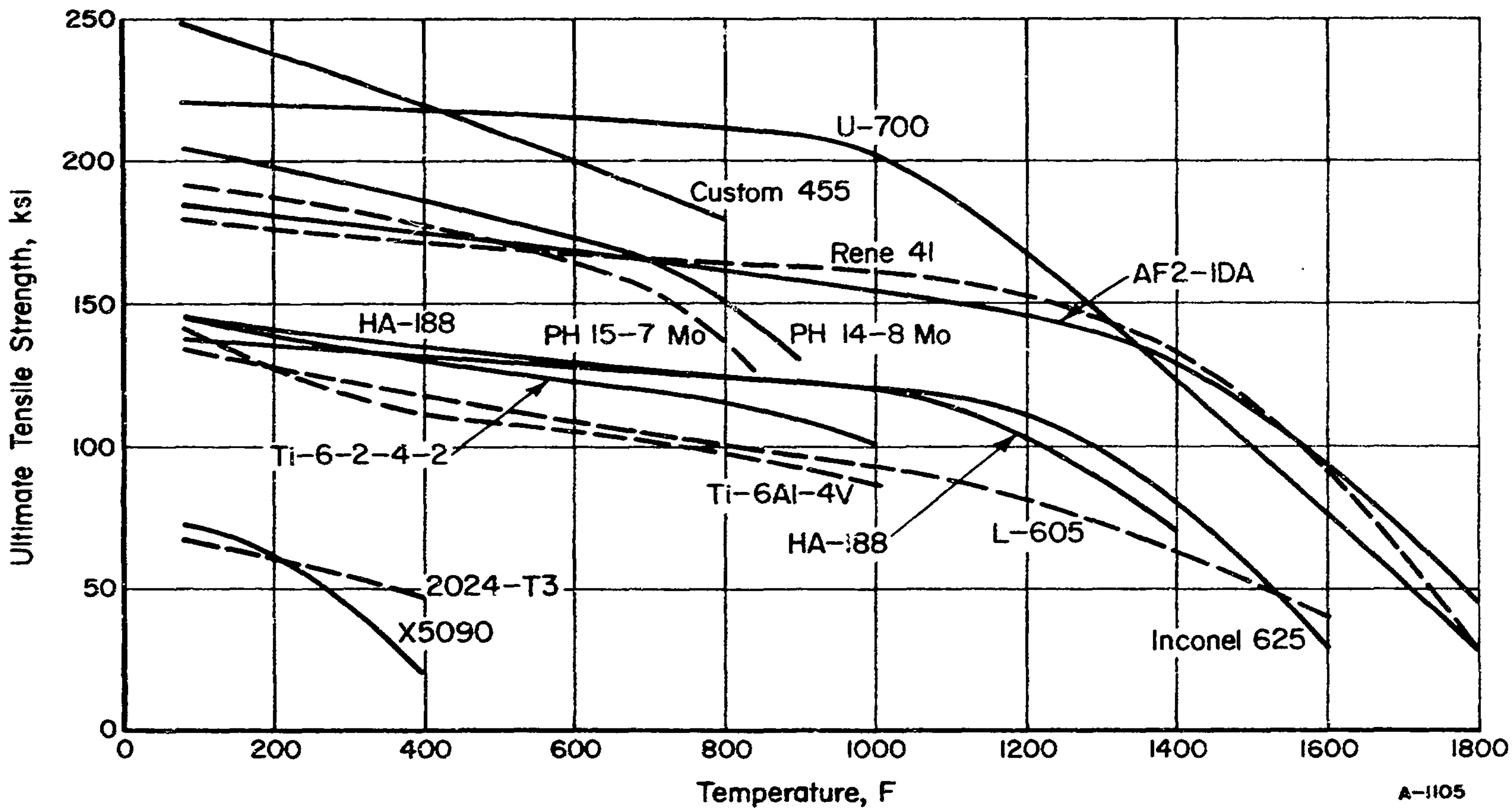

FIGURE 94. ULTIMATE TENSILE STRENGTH AS A FUNCTION OF TEMPERATURE

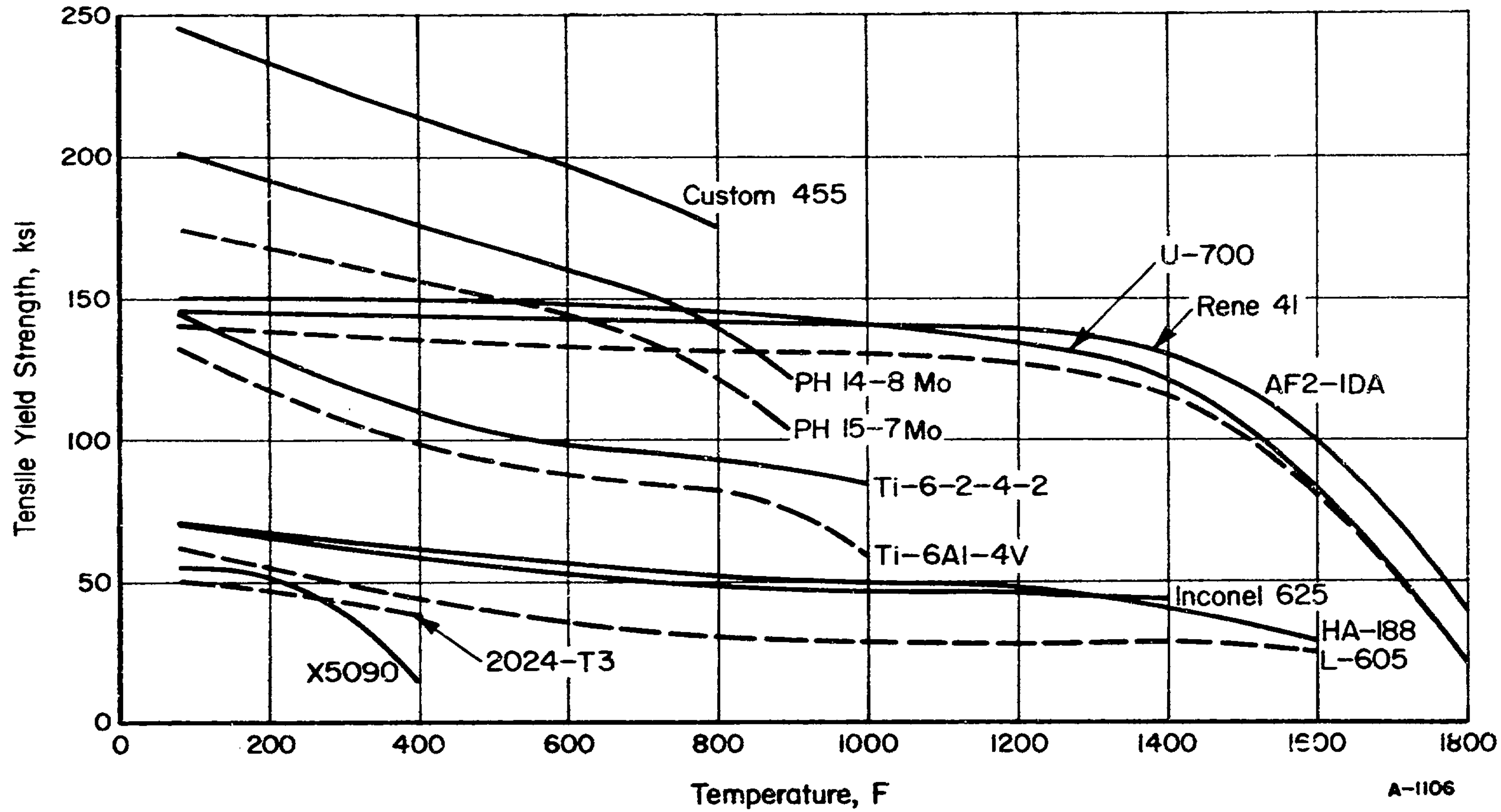

FIGURE 95. TENSILE YIELD STRENGTH AS A FUNCTION OF TEMPERATURE

REFERENCES

1. Deel, O. L., and Hyler, W. S., "Engineering Data on Newly Developed Structural Materials", AFML-TR-67-418 (April 1968).

2. Deel, O. L., and Hyler, W. S., "Engineering Data on Newly Developed Structural Materials", AFML-TR-68-211 (July 1968).

3. Deel, O. L., and Mindlin, H., "Engineering Data on New and Emerging Structural Materials", AFML-TR-70-252 (October 1970).

4. "Standard Elevated Temperature Testing Procedures for Metallic Materials", ARTC-13, prepared by the Aerospace Research and Testing Committee (July 1957, revised March 1958 and June 1959).

5. "Evaluation of Test Methods for Refractory Metal Sheet Material", MAB 192-M (April 1963).

6. Kelley, E. W., "Manufacturing Process for Improved High-Strength Superalloy Sheet", AFML-TR-69-114 (June 1969).

Inconel 625 Alloy

Inconel 625 is a relatively new product of Huntington Alloy Products Division of The International Nickel Company, Inc. It is reported to have high strength and toughness from cryogenic temperatures to 2000 F. It is a nonmagnetic alloy deriving its strength from the stiffening effect of molybdenum and columbium on its nickel-chromium matrix. It has good oxidation resistance and is virtually immune to chloride-ion stress-corrosion cracking.

Inconel 625 is readily fabricated by common industrial practices and has excellent weld qualities, requiring no postweld thermal treatment for maintenance of its corrosion resistance. The alloy has already been used in numerous aerospace applications and is currently being evaluated for use in the chemical and marine fields.

Standard mill forms including sheet, strip, rods and bars, shapes, tube and plate are available.

The nominal composition of Inconel 625 is as follows.

C	Mn	Fe	S	Si	Cr	Al	Ti
0.10	0.50	5.0	0.015	0.50	20.0-23.0	0.40	0.40

Mo	Co	P	Cb + Ta	Ni
8.0-10.0	1.0 max	0.015	3.5-4.15	Balance

Inconel 625 Data[(a)]

Condition: Annealed
Thickness: 0.125-inch sheet

Properties	RT	800	1200	1600
	Temperature, F			
Tension				
TUS (longitudinal), ksi	138.7	123.3	112.3	29.8
TUS (transverse), ksi	136.7	122.3	113.0	29.3
TYS (longitudinal), ksi	69.5	53.3	48.9	29.7
TYS (transverse), ksi	69.6	53.6	49.6	29.0
e_t (longitudinal), percent in 2 in.	51.1	50.0	97.0	123.0
e_t (transverse), percent in 2 in.	50.0	51.0	81.3	118.0
E_t (longitudinal), 10^6 psi	28.3	24.1	22.5	14.6
E_t (transverse), 10^6 psi	30.3	25.0	24.7	18.1
Compression				
CYS (longitudinal), ksi	71.5	57.5	55.6	31.5
CYS (transverse), ksi	73.4	59.0	54.9	31.4
E_c (longitudinal), 10^6 psi	29.1	24.0	24.8	15.5
E_c (transverse), 10^6 psi	30.7	26.2	25.2	14.2
Shear[(b)]				
SUS (longitudinal), ksi	114.5	U[(e)]	U	U
SUS (transverse), ksi	115.8	U	U	U
Bend[(c)]				
Longitudinal, minimum radius	T/5	U	U	U
Transverse, minimum radius	T/5	U	U	U
Fracture Toughness, K_c[(d)]				
ksi$\sqrt{\text{in.}}$	(d)	U	U	U
Axial Fatigue (transverse)[(f)]				
Unnotched, R = 0				
10^3 cycles, ksi	140	120	100	U
10^5 cycles, ksi	106	102	78	U
10^7 cycles, ksi	72	96	68	U
Notched, K_t = 3.0, R = 0.1				
10^3 cycles, ksi	130	114	80	U
10^5 cycles, ksi	60	52	48	U
10^7 cycles, ksi	40	40	40	U
Creep (transverse)				
0.2% plastic deformation, 100 hr	NA	(h)	58	1.4
0.2% plastic deformation, 1000 hr	NA	(h)	50	0.8

Inconel 625 Data (continued)

Properties	RT	800	1200	1600
	Temperature, F			
Stress Rupture (transverse)				
Rupture, 100 hr	NA	>120	72	59
Rupture, 1000 hr	NA	>120	7	3.5
Stress Corrosion				
80% TYS, 1000-hr maximum	No cracks[g]			
Coefficient of Thermal Expansion				
7.4×10^{-6} in./in./F (70 to 500 F)				
8.7×10^{-6} in./in./F (70 to 1500 F)				
Density				
0.305 lb/in.^{3}				

(a) Values are average of triplicate tests conducted at Battelle under the subject contract unless otherwise indicated. Fatigue, creep, and stress-rupture values are from curves generated using the results of a greater number of tests.

(b) Single-shear sheet-type specimen.

(c) Specimens tested at RT, +32 F, and -90 F. No cracks at either temperature.

(d) Specimens were full sheet thickness x 18 in. x 48 in. with EDM flaw in center. Average K_c was 158 ksi$\sqrt{\text{in.}}$ The net section yield stress at fracture was greater than the tensile yield strength of the material; therefore, the K values are considered not valid.

(e) U, unavailable; NA, not applicable.

(f) "R" represents the algebraic ratio of minimum stress to maximum stress in one cycle; that is, $R = S_{min}/S_{max}$. "K_t" represents the Neuber-Peterson theoretical stress concentration factor.

(g) Room-temperature three-point bend test. Alternate immersion in 3-1/2% NaCl.

(h) Extensometer inoperative due to large initial strain; negative creep occurred.

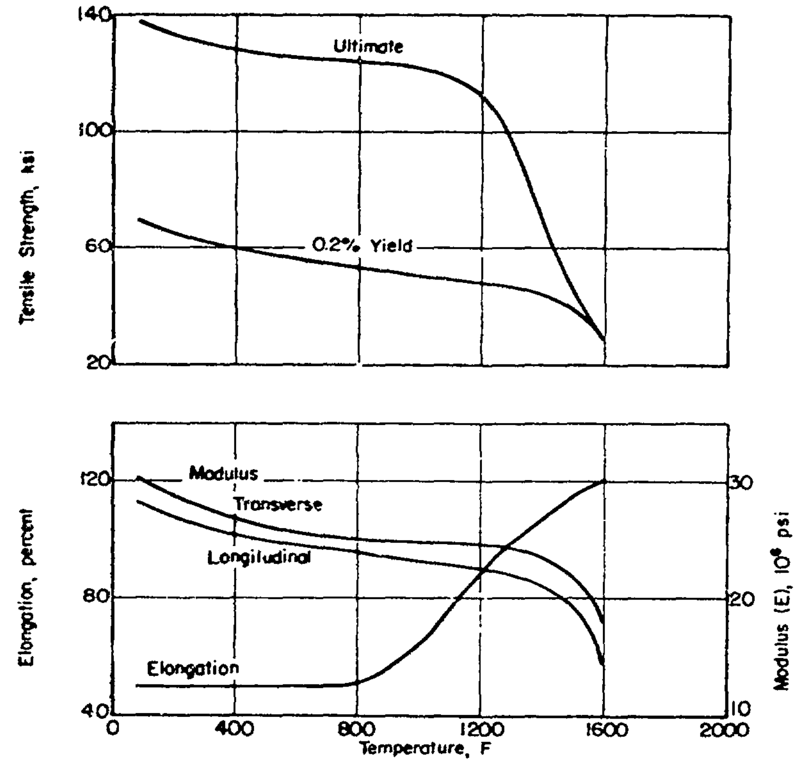

FIGURE 1. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF INCONEL 625 SHEET

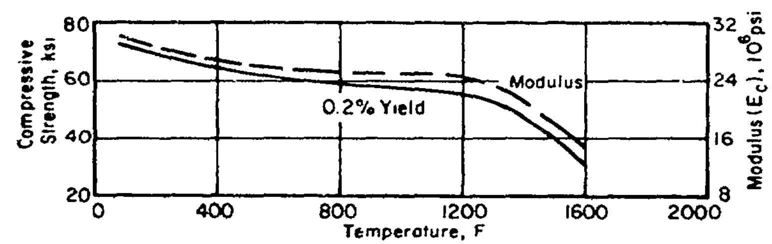

FIGURE 2 EFFECT OF TEMPERATURE ON THE COMPRESSIVE PROPERTIES OF INCONEL 625 SHEET

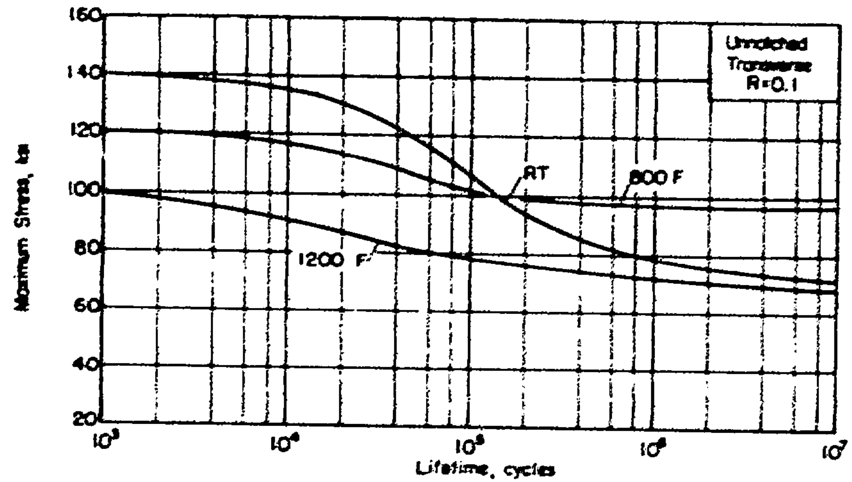

FIGURE 3. AXIAL-LOAD FATIGUE RESULTS FOR INCONEL 625 SHEET

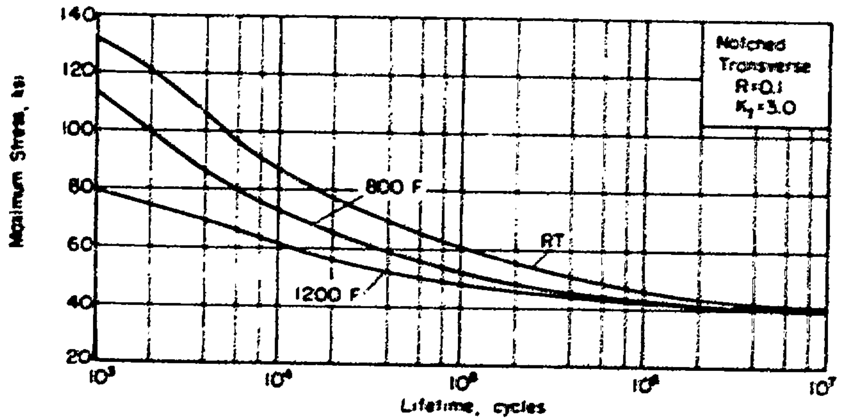

FIGURE 4. AXIAL-LOAD FATIGUE RESULTS FOR NOTCHED (K_t=3.0) INCONEL 625 SHEET

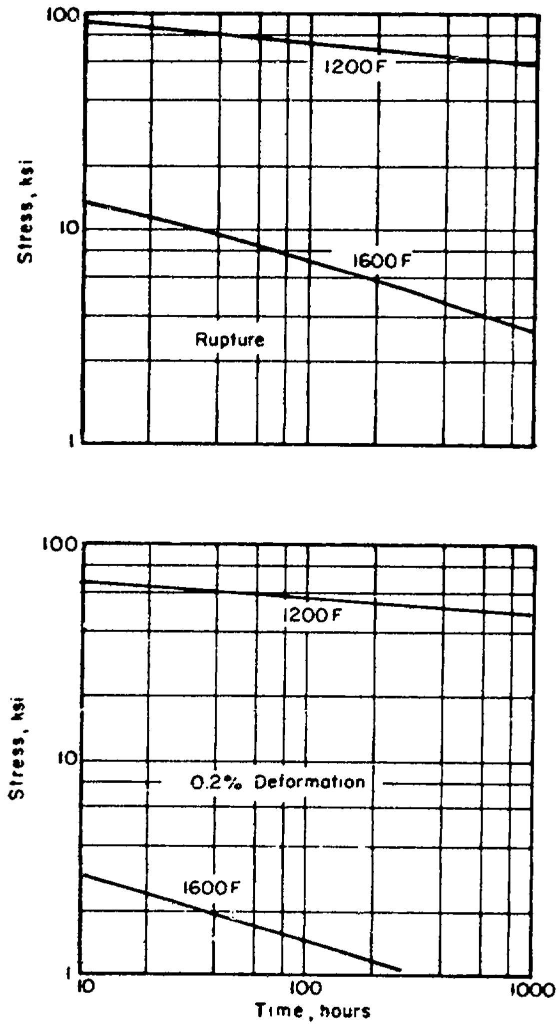

FIGURE 5 STRESS-RUPTURE AND PLASTIC DEFORMATION CURVES FOR INCONEL 625 SHEET

AF2-1DA Alloy

AF2-1DA is a recently developed high-temperature nickel-base alloy. It was developed by the Universal-Cyclops Specialty Steel Division under Air Force Contract AF 33(615)-1729. Early development was in thick section form for turbine wheel/bucket applications. A "data sheet" for extruded material was issued under an earlier contract (F33615-69-C-1115).

A sheet manufacturing process for AF2-1DA alloy was developed at Union Carbide, also under Air Force sponsorship (Contract AF 33(615)-3687). The sheet material evaluated and reported herein was supplied by the Air Force from this program. The heat-treatment used for the material was 2225F/2 hr/RAC + 1950F/2 hr AC + 1400F/16 hr/AC. The composition of the material was as follows:

Carbon	[illegible]
Molybdenum	2.94
Zirconium	0.10
Tantalum	1.40
Tungsten	[illegible]
Cobalt	9.94
Chromium	12.14
Aluminum	[illegible]
Titanium	3.14
Boron	.014
Nickel	Balance

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AF2-1DA Data[a]

Condition: STA
Thickness: 0.060-inch sheet

Properties	Temperature, F RT	1000	1400	1800
Tension				
TUS (longitudinal), ksi	191.7	153.0	130.0	46.4
TUS (transverse), ksi	180.0	151.7	131.3	48.2
TYS (longitudinal), ksi	144.3	137.3	130.0	37.4
TYS (transverse), ksi	142.3	137.0	130.0	40.2
e_t (longitudinal), percent in 2 in.	12.0	2.3	0.8	7.8
e_t (transverse), percent in 2 in.	12.0	1.8	1.0	5.2
E_t (longitudinal), 10^6 psi	31.9	28.1	24.3	18.2
E_t (transverse), 10^6 psi	30.8	28.2	24.0	18.7
Compression				
CYS (longitudinal), ksi	153.0	143.0	136.0	35.5
CYS (transverse), ksi	153.0	143.3	132.0	38.9
E_c (longitudinal), 10^6 psi	31.3	34.3	25.8	17.6
E_c (transverse), 10^6 psi	32.4	29.6	26.4	18.2
Shear[b]				
SUS (longitudinal), ksi	120.5	U[c]	U	U
SUS (transverse), ksi	120.0	U	U	U
Fracture Toughness, K_c[d]				
ksi$\sqrt{\text{in.}}$	(d)	U	U	U
Axial Fatigue (transverse)[e]				
Unnotched, R = 0.1				
10^3 cycles, ksi	190	160	80	U
10^5 cycles, ksi	115	108	58	U
10^7 cycles, ksi	60	74	36	U
Notched, K_t = 3.0, R = 0.1				
10^3 cycles, ksi	150	106	64	U
10^5 cycles, ksi	54	43	34	U
10^7 cycles, ksi	30	36	24	U
Creep (transverse)				
0.2% plastic deformation, 100 hr, ksi	NA	108	43	2.9
0.2% plastic deformation, 1000 hr, ksi	NA	106	20	2.1

AF2-1DA Data (continued)

Properties		Temperature, F		
	RT	1000	1400	1800
Stress Rupture (transverse)				
Rupture, 100 hr, ksi	NA	115	61	9
Rupture, 1000 hr., ksi	NA	109	40	6.5
Stress Corrosion				
80% TYS, 1000-hr maximum	No cracks(f)	U	U	U

Coefficient of Thermal Expansion

8.3×10^{-6} in./in./F (68 to 1300 F)

Density

0.292 lb/in.^{3}

(a) Data are average of triplicate tests conducted at Battelle under the subject contract unless otherwise indicated. Fatigue, creep, and stress-rupture values are from data curves generated using a greater number of tests.

(b) Single-shear clevis-type specimen.

(c) U, unavailable; NA, not applicable.

(d) GFM material quantity not sufficient for K_c tests.

(e) "R" represents the algebraic ratio of the minimum stress to the maximum stress in one cycle; that is, $R = S_{min}/S_{max}$. "K_t" represents the Neuber-Peterson theoretical stress-concentration factor.

(f) Three-point bend test. Alternate immersion in 3-1/2 percent NaCl.

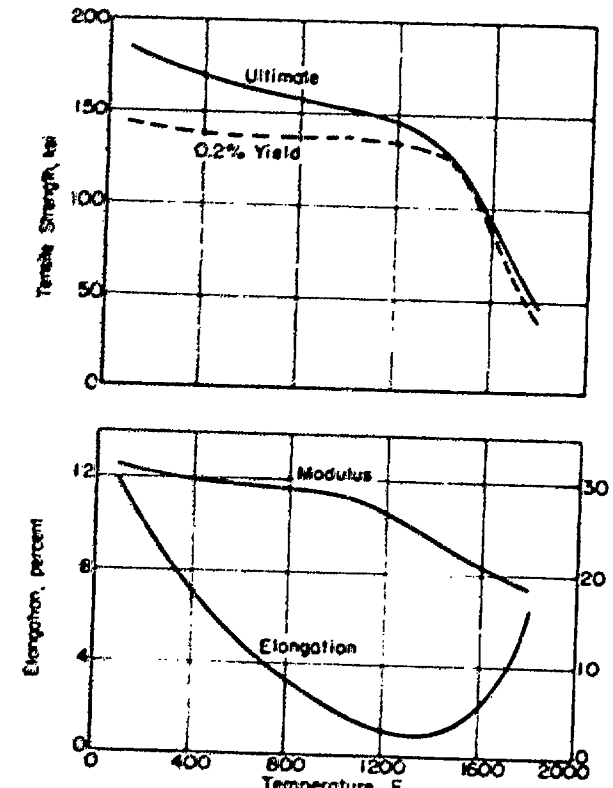

FIGURE 1. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF AF2-1DA SHEET

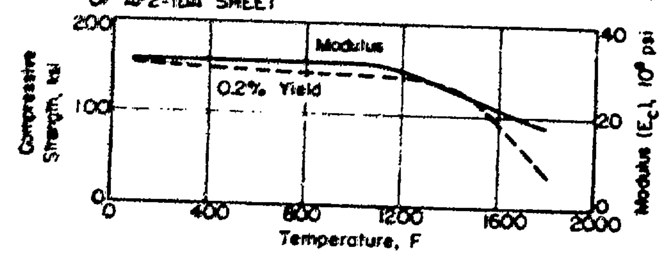

FIGURE 2. EFFECT OF TEMPERATURE ON THE COMPRESSIVE PROPERTIES OF AF2-1DA SHEET

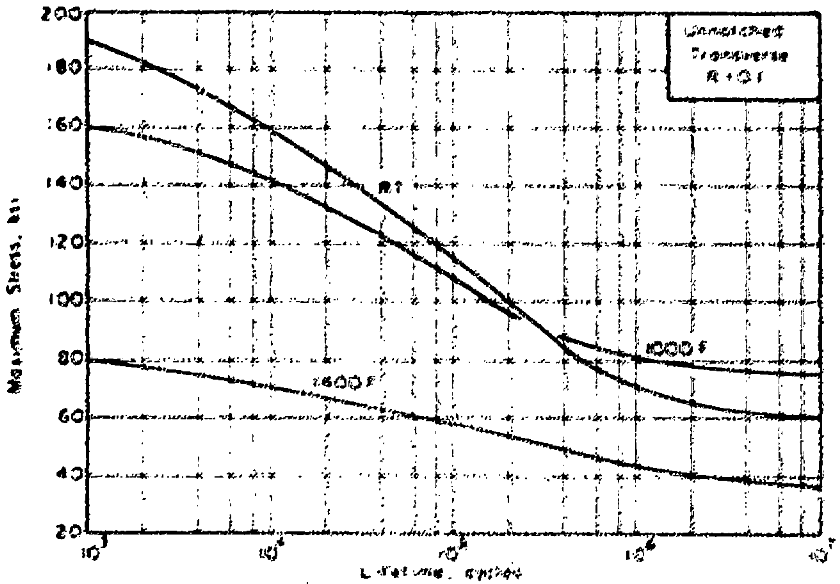

FIGURE 3 AXIAL-LOAD FATIGUE RESULTS FOR UNNOTCHED AF2-1DA SHEET AT THREE TEMPERATURES

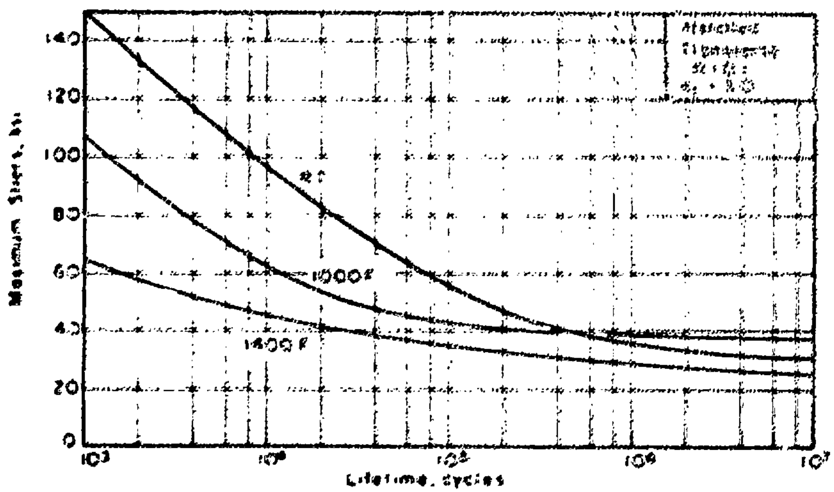

FIGURE 4 AXIAL-LOAD FATIGUE RESULTS FOR NOTCHED (K_t = 3.0) AF2-1DA SHEET AT THREE TEMPERATURES

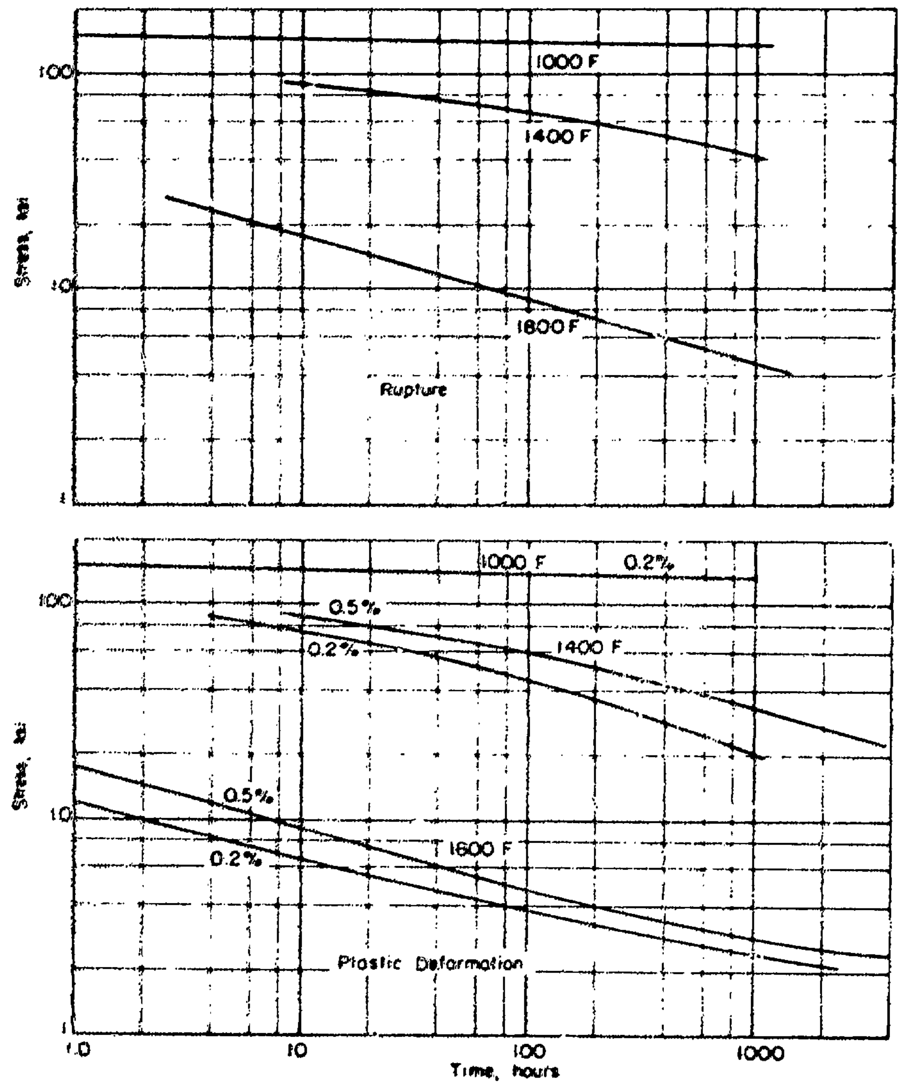

FIGURE 5. STRESS-RUPTURE AND PLASTIC DEFORMATION CURVES FOR AF2-1DA SHEET AT THREE TEMPERATURES

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Custom 455 Data[a]

Condition: Aged
Thickness: 1-inch-diameter Bar

Property	Temperature, F RT	400	600	800
Tension				
TYS (longitudinal), ksi	248.4	215.9	201.2	180.6
TUS (longitudinal), ksi	247.4	214.4	197.2	174.1
e, (longitudinal), percent in 2 in.	10.0	10.6	11.8	14.7
RA (longitudinal), percent	45.3	50.0	54.2	63.2
E_t (longitudinal), 10^6 psi	28.3	27.8	26.7	26.5
Compression				
CYS (longitudinal), ksi	255.4	219.3	202.0	177.7
E_c (longitudinal), 10^6 psi	29.7	27.7	26.5	23.9
Shear[b]				
SUS (longitudinal), ksi	152.0	U[d]	U	U
Impact[c]				
V-notch Charpy, ft lb	15.0	U	U	U
Fracture Toughness[e]				
K_{Ic}, ksi$\sqrt{in.}$	55.6	U	U	U
Axial Fatigue (Longitudinal)[f]				
Unnotched, R = 0.1				
10^3 cycles, ksi	240	220	U	188
10^5 cycles, ksi	131	127	U	123
10^7 cycles, ksi	120	120	U	104
Notched, K_t = 3.0, R = 0.1				
10^3 cycles, ksi	150	134	U	133
10^5 cycles, ksi	45	60	U	60
10^7 cycles, ksi	30	44	U	44
Creep (Longitudinal)				
0.2% plastic deformation, 100 hr	NA	207	163	44[g]
0.2% plastic deformation, 1000 hr	NA	203	155	30[g]
Stress Rupture (Longitudinal)				
Rupture, 100 hr	NA	216	193	99[g]
Rupture, 1000 hr	NA	215	188	77[g]
Stress Corrosion				
60% TYS, 1000 hr max	No cracks[h]			

Properties	RT	Temperature, F 400	600	800
Coefficient of Thermal Expansion				
6.08×10^{-6} in./in./F (72 to 400 F)				
6.57×10^{-6} in./in./F (72 to 800 F)				
Density				
0.280 lb/in.^{3}				

(a) Data are average of triplicate tests conducted at Battelle under the subject contract unless otherwise indicated. Fatigue, creep, and stress-rupture values are from curves generated using a greater number of tests.

(b) Double-shear pin-type specimen, 0.250-inch diameter.

(c) 10.0 at -90 F.

(d) U, unavailable; NA, not applicable.

(e) Slow-bend chevron-notched-type specimen.

(f) "R" represents the algebraic ratio of minimum stress to maximum stress in one cycle; that is, $R = S_{min}/S_{max}$. "K_t" represents the Neuber-Peterson theoretical stress concentration factor.

(g) ..ta for 850 F.

(h) Room-temperature three-point bend test. Alternate immersion in 3-1/2 percent NaCl.

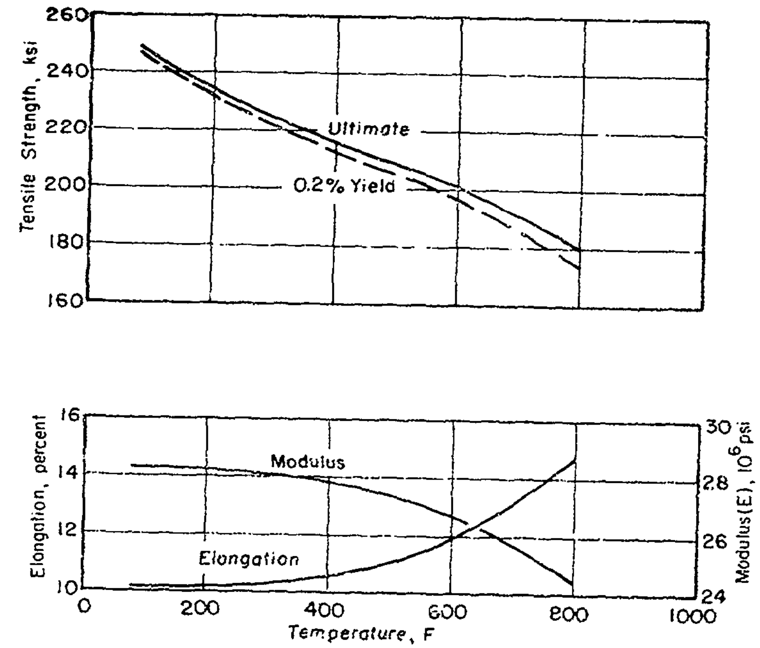

FIGURE 1. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF CUSTOM 455 ROUND BAR

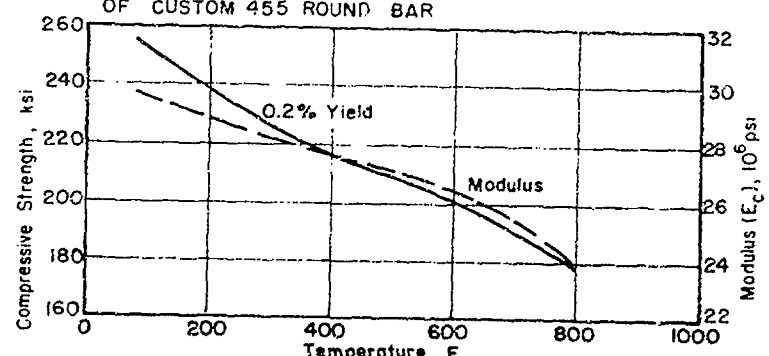

FIGURE 2. EFFECT OF TEMPERATURE ON THE COMPRESSIVE PROPERTIES OF CUSTOM 455 ROUND BAR

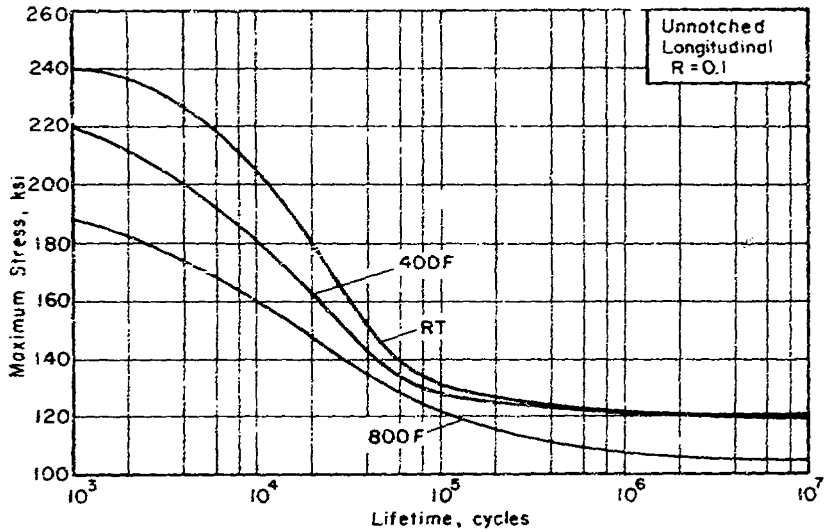

FIGURE 3 AXIAL-LOAD FATIGUE RESULTS FOR UNNOTCHED CUSTOM 455 ROUND BAR AT THREE TEMPERATURES

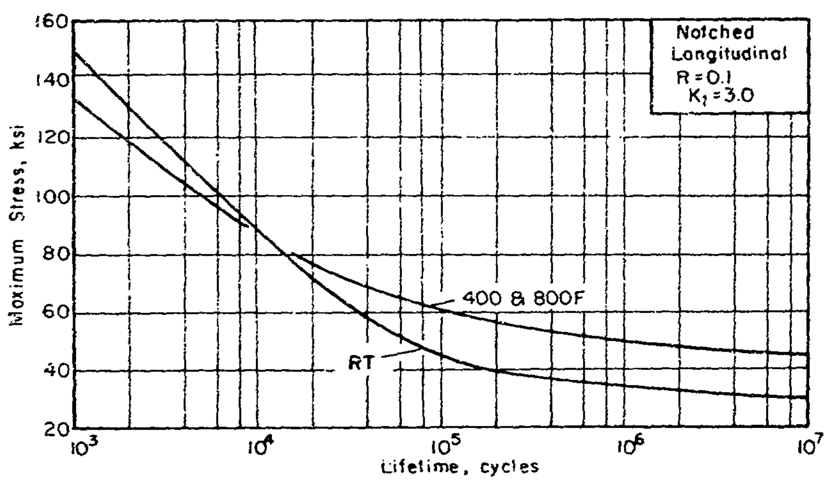

FIGURE 4. AXIAL-LOAD FATIGUE RESULTS FOR NOTCHED ($K_t = 3.0$) CUSTOM 455 ROUND BAR AT THREE TEMPERATURES

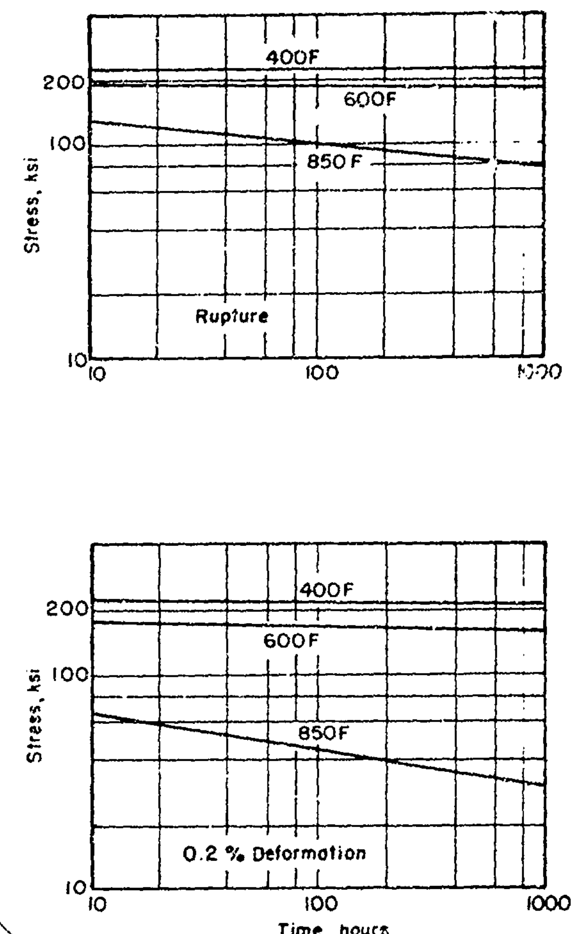

FIGURE 5. STRESS-RUPTURE AND PLASTIC DEFORMATION CURVES FOR CUSTOM 455 ROUND BAR

HA-188 Alloy

Haynes Alloy 188 is a new cobalt-base alloy development of the Stellite Division of The Cabot Corporation. It is reported to have excellent high-temperature strength and oxidation resistance, and good post-aging ductility. It can be strengthened and hardened by cold work. The alloy can be welded by conventional techniques and exhibits good restraint-welding characteristics. Studies are now in progress to define the aging characteristics of this alloy.

The nominal composition of Alloy 188 is as follows.

Cr	W	C	Ni	Si	Mn	Fe	La	Co
22.0	14.0	0.08	22.0	0.20	0.75	1.5	0.08	Balance

HA-188 Data[a]

Condition: Annealed
Thickness: 0.078-inch sheet

Properties	Temperature, F RT	600	1000	1400
Tension				
TUS (longitudinal), ksi	146.0	128.5	119.5	70.1
TUS (transverse), ksi	145.5	127.5	118.0	70.7
TYS (longitudinal), ksi	78.5	55.2	51.3	46.9
TYS (transverse), ksi	68.7	49.0	45.7	44.2
e_t (longitudinal), percent in 2 in.	60.0	63.5	56.5	50.5
e_t (transverse), percent in 2 in.	59.8	63.5	56.5	48.7
E_t (longitudinal), 10^6 psi	35.1	36.4	30.5	26.3
E_t (transverse), 10^6 psi	3 .6	33.1	32.5	24.2
Compression				
CYS (longitudinal), ksi	50.0	43.5	41.3	44.2
CYS (transverse), ksi	73.8	54.9	49.5	46.2
E_c (longitudinal), 10^6 psi	33.2	30.1	30.5	24.5
E_c (transverse), 10^6 psi	33.0	29.5	29.0	25.7
Shear[b]				
SUS (longitudinal), ksi	132.8	U[e]	U	U
SUS (transverse), ksi	137.1	U	U	U
Bend[c]				
Longitudinal, minimum radius	T/5	U	U	U
Transverse, minimum radius	T/5	U	U	U
Fracture Toughness, K_c				
ksi$\sqrt{in.}$	(d)	U	U	U
Axial Fatigue (transverse)[f]				
Unnotched, R = 0.1				
10^3 cycles, ksi	145	U	120	70
10^5 cycles, ksi	116	U	91	50
10^7 cycles, ksi	80	U	66	45
Notched, K_t = 3.0, R = 0.1				
10^3 cycles, ksi	138	U	94	65
10^5 cycles, ksi	67	U	60	36
10^7 cycles, ksi	40	U	40	30

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HA-188 Data (continued)

Properties	RT	Temperature, F 800	1200	1600
Creep (transverse)				
0.2% plastic deformation, 100 hr	NA	116	44	9
0.2% plastic deformation, 1000 hr	NA	115	33	7
Stress Rupture, transverse				
Rupture, 100 hr	NA	116.5	65	16
Rupture, 1000 hr	NA	115.5	50	11
Stress Corrosion				
80% TYS, 1000-hour maximum	No cracks(g)			
Coefficient of Thermal Expansion				
6.8×10^{-6} in./in./F (78 to 600 F)				
9.2×10^{-6} in./in./F (78 to 1400 F)				
Density				
0.333 lb/in.^{3}				

(a) Values are average of triplicate tests conducted at Battelle under the subject contract unless otherwise indicated. Fatigue, creep, and stress-rupture values are from curves generated using the results of a greater number of tests.

(b) Single-shear sheet-type specimens

(c) Specimens tested at RT, +32, and -90 F. No cracks at either temperature.

(d) Specimens were full sheet thickness x 18 in. x 48 in. with EDM flaw in center. Average K_c was 175 ksi$\sqrt{\text{in.}}$ The net section yield stress at fracture was greater than the tensile yield strength of the material; therefore, the K values are considered not valid.

(e) U, unavailable; NA, not applicable.

(f) "R" represents the algebraic ratio of minimum stress to maximum stress in one cycle; that is, $R = S_{min}/S_{max}$. "K_t" represents the Neuber-Peterson theoretical stress-concentration factor.

(g) Room-temperature three-point bend test. Alternate immersion in 3-1/2 percent NaCl.

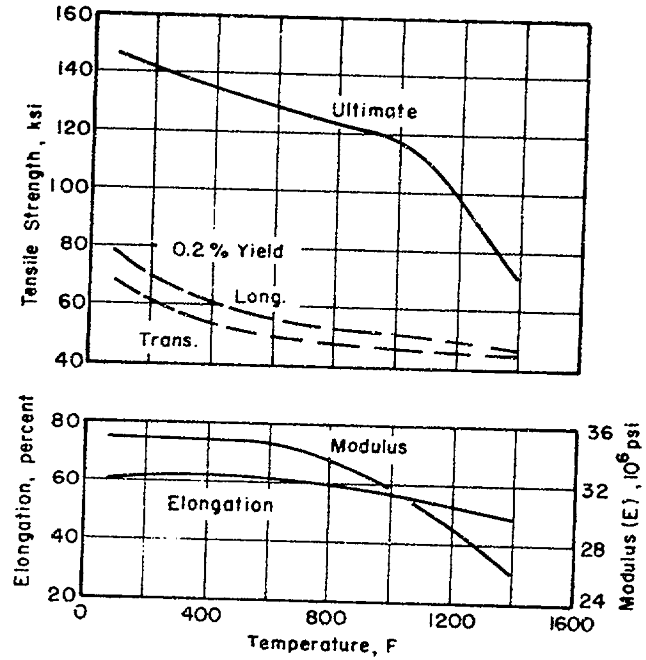

FIGURE 1. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF HA-188 SHEET

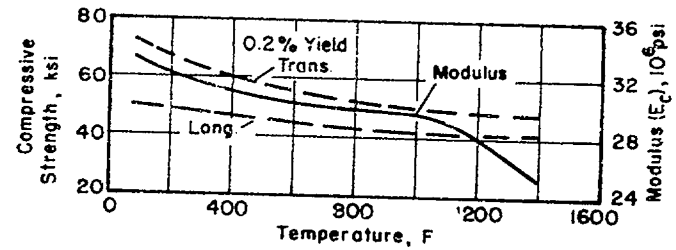

FIGURE 2. EFFECT OF TEMPERATURE ON THE COMPRESSIVE PROPERTIES OF HA-188 SHEET

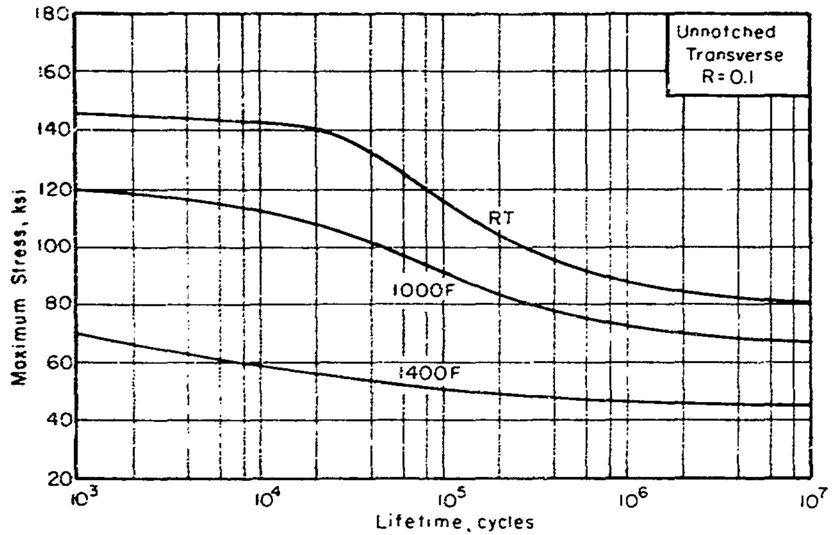

FIGURE 3 AXIAL-LOAD FATIGUE RESULTS FOR UNNOTCHED HA-188 SHEET AT THREE TEMPERATURES

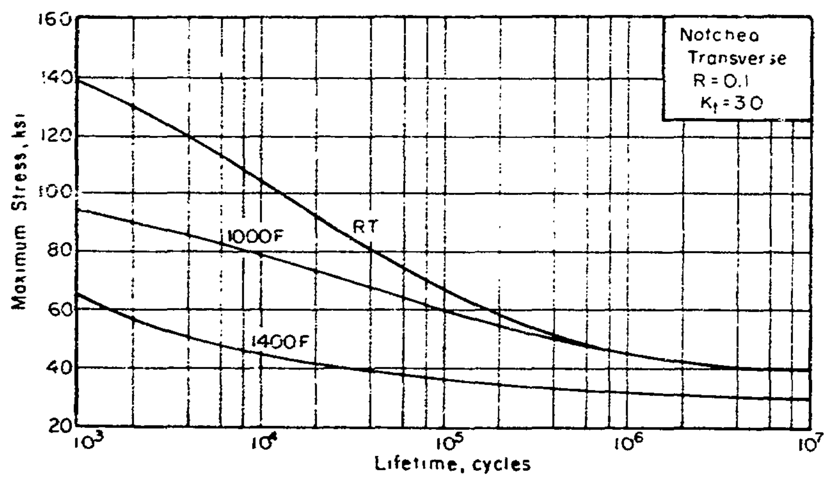

FIGURE 4 AXIAL-LOAD FATIGUE RESULTS FOR NOTCHED (K_t=3.0) HA-188 SHEET AT THREE TEMPERATURES

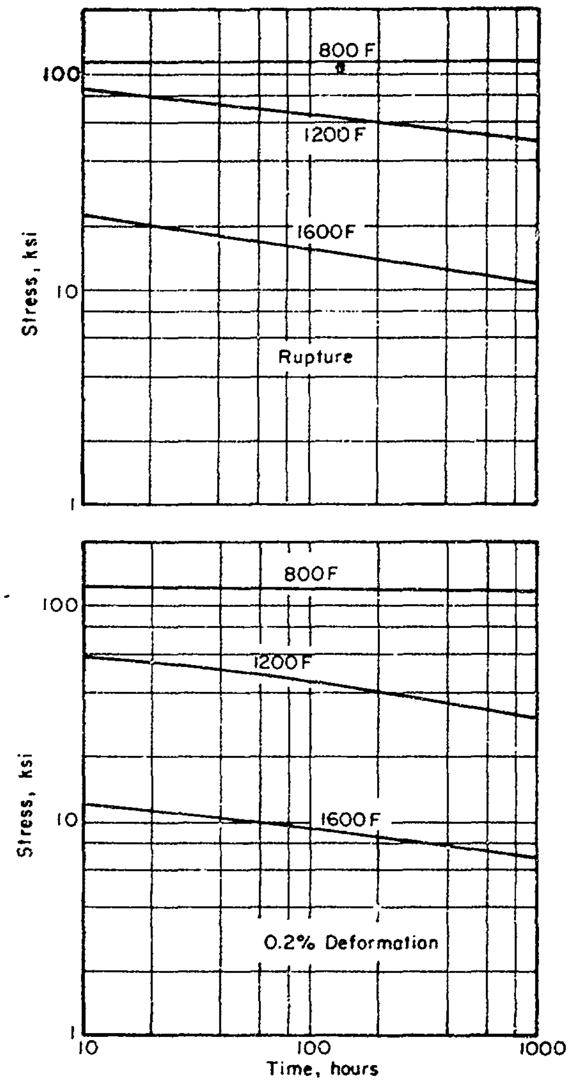

FIGURE 5. STRESS-RUPTURE AND PLASTIC DEFORMATION CURVES FOR HA-188 SHEET

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X5090-H38 Aluminum Alloy

Alloy X5090 is a development of the Aluminum Division, Olin Corporation. As a basic Aluminum-7% Magnesium alloy, it is designed to offer exceptional mechanical properties in the cold-worked and stabilized temper without susceptibility to stress corrosion cracking. A combination of controlled chemistry of minor elements and controlled thermal processing has resulted in light gage, full-hard sheet material with mechanical properties in excess of those of 2024-T3. The alloy, as reported by Olin, is characterized by low density, excellent fracture toughness, excellent fatigue strength, and excellent general corrosion resistance, as well as freedom from susceptibility to stress corrosion cracking.

Composition limits of this alloy are as follows:

Si	0.50 max
Fe	0.50 max
Cu	0.25 max
Mn	0.35 max
Mg	6.0 to 8.0
Cr	0.05 to 0.30
Zn	0.20 max
Ti	0.015 max
Be	0.001 to 0.02
B	0.001 to 0.050
Others	0.15 max

The H38 condition is 75 percent cold-rolled and stabilized.

X5090 Aluminum Data(a)

Condition: -H38
Thickness: 0.025-inch sheet

Properties	Temperature, F			
	RT	200	325	400
Tension				
TUS (longitudinal), ksi	73.9	62.9	35.9	19.2
TUS (transverse), ksi	72.3	62.0	41.5	22.9
TYS (longitudinal), ksi	58.7	54.6	30.5	13.3
TYS (transverse), ksi	52.8	50.7	37.6	19.9
e_t (longitudinal), percent in 2 in.	6.8	13.0	47.0	79.3
e_t (transverse), percent in 2 in.	9.0	21.0	39.0	49.3
E_t (longitudinal), 10^6 psi	12.9	9.4	7.1	4.5
E_t (transverse), 10^6 psi	10.5	9.4	7.5	5.1
Compression				
CYS (longitudinal), ksi	57.5	58.0	41.6	19.1
CYS (transverse), ksi	63.5	66.1	47.1	28.9
E_c (longitudinal), 10^6 psi	10.5	10.6	8.1	6.8
E_c (transverse), 10^6 psi	10.7	11.2	8.2	6.7
Shear(b)				
SUS (longitudinal), ksi	43.0	U(c)	U	U
SUS (transverse), ksi	41.9	U	U	U
Bend				
Longitudinal, minimum radius	4t	U	U	U
Transverse, minimum radius	3.5t	U	U	U
Fracture Toughness, K_c(d) ksi$\sqrt{\text{in.}}$	49	U	U	U
Axial Fatigue (transverse)				
Unnotched, R = 0.1(e)				
10^3 cycles, ksi	73	60	50	U
10^5 cycles, ksi	43	37	30	U
10^7 cycles, ksi	30	26	13	U
Notched, K_t = 3.0, R = 0.1				
10^3 cycles, ksi	50	48	38	U
10^5 cycles, ksi	22	18	13	U
10^7 cycles, ksi	14	12	5	U
Creep (transverse)				
0.5% plastic deformation, 100 hr	NA	25	6	3
0.5% plastic deformation, 1000 hr	NA	8	3.5	2

X5090 Aluminum Data (Continued)

Properties	RT	200	325	400
	Temperature, F			
<u>Stress Rupture (transverse)</u>				
Rupture, 100 hr	NA	41	15	7
Rupture, 1000 hr	NA	35	10	4.5
<u>Stress Corrosion</u>				
80% TYS, 1000-hour maximum	No cracks(f)			
<u>Coefficient of Thermal Expansion</u>				
12.8×10^{-6} in./in./F (68 to 212 F)				
<u>Density</u>				
0.095 lb/in.^{3}				

(a) Each value given is the average of at least three tests conducted at Battelle under the subject contract, unless otherwise indicated. Fatigue, creep, and stress-rupture values are from curves generated using a greater number of tests.

(b) Single-shear sheet-type test.

(c) U, unavailable; NA, not applicable.

(d) Specimens were full sheet thickness x 18 in. x 48 in. with EDM flaw in center. The net section yield stress at fracture was less than the tensile yield strength of the material; therefore, the K values are considered valid.

(e) "R" represents the algebraic ratio of minimum stress to maximum stress in one cycle; i.e., $R = S_{min}/S_{max}$. "K_t" represents the Neuber-Peterson theoretical stress concentration factor.

(f) Room-temperature three-point bend test. Alternate immersion in 3½ percent NaCl.

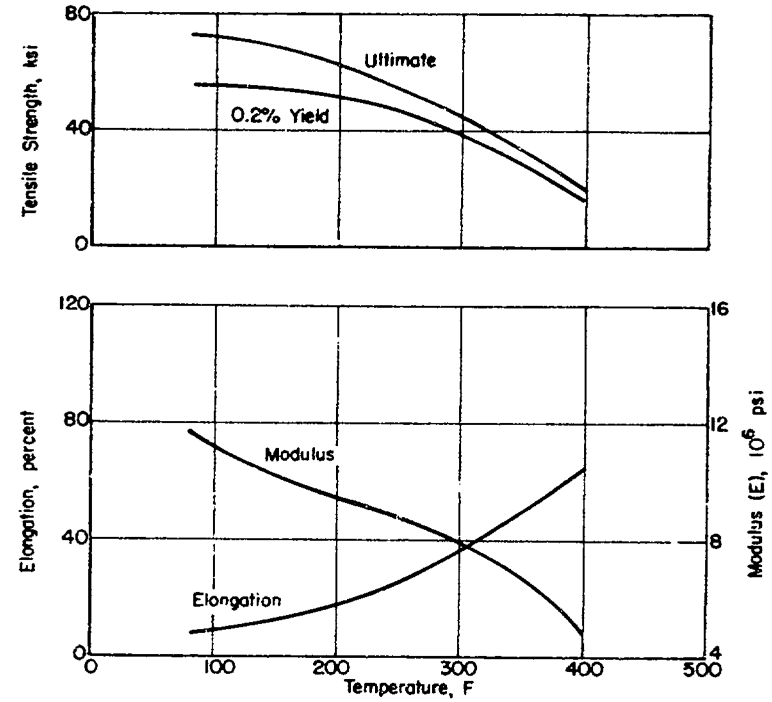

FIGURE 1. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF X5090 ALUMINUM ALLOY

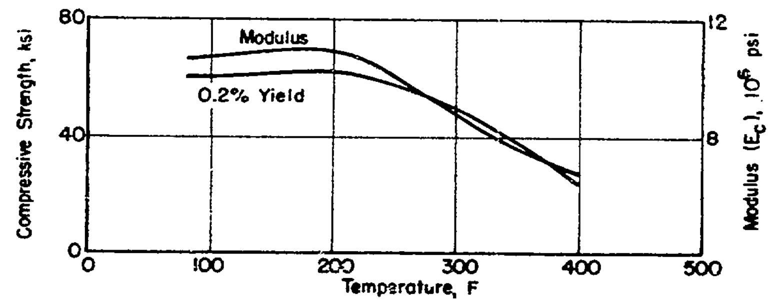

FIGURE 2. EFFECT OF TEMPERATURE ON THE COMPRESSIVE PROPERTIES OF X5090 ALUMINUM ALLOY

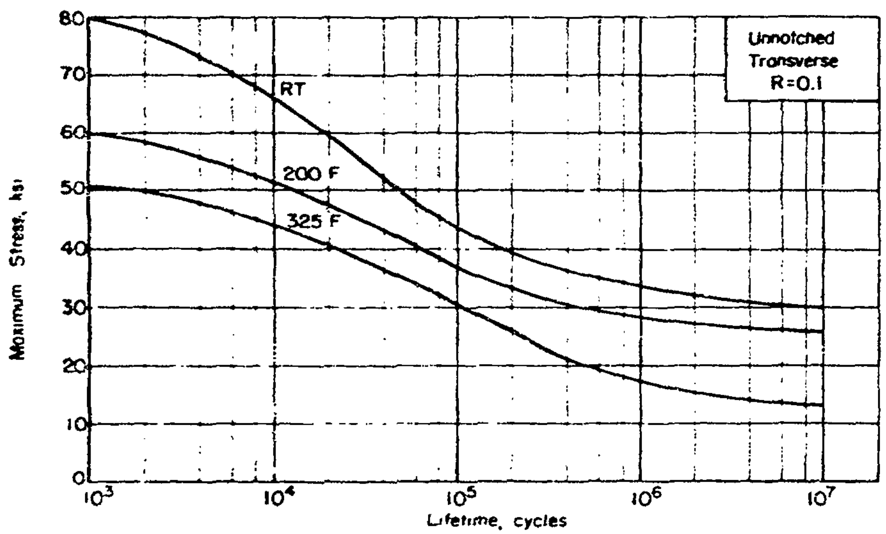

FIGURE 3 AXIAL-LOAD FATIGUE RESULTS FOR UNNOTCHED X5090 ALUMINUM SHEET AT THREE TEMPERATURES

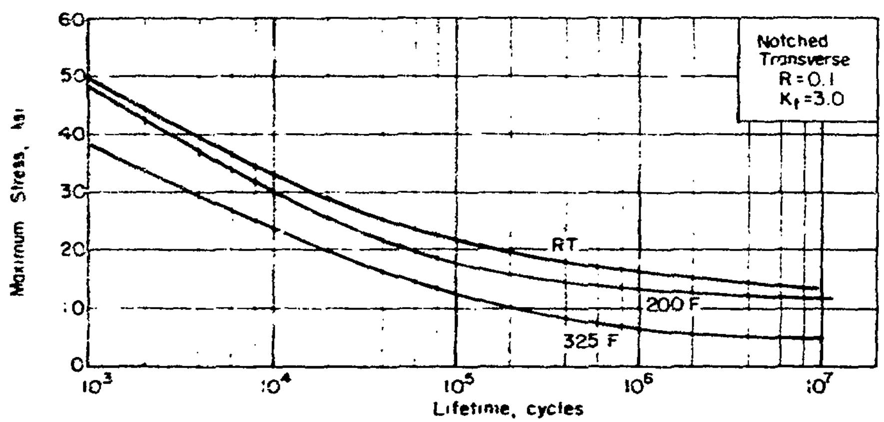

FIGURE 4 AXIAL-LOAD FATIGUE RESULTS FOR NOTCHED (K_t=3.0) X5090 ALUMINUM SHEET AT THREE TEMPERATURES

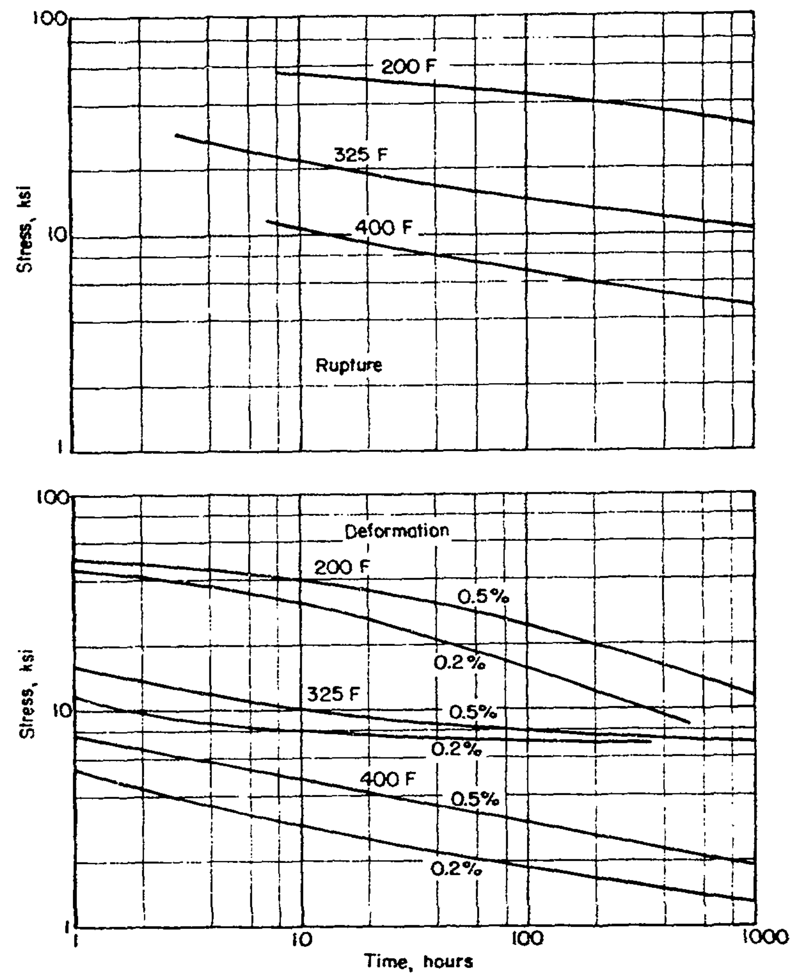

FIGURE 5. STRESS-RUPTURE AND PLASTIC DEFORMATION CURVES FOR X-5090 ALUMINUM SHEET AT THREE TEMPERATURES

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Udimet 700 Alloy

Udimet 700 is one of the older heat-resistant nickel-base alloys that has seen limited use in engines as forging and bar products. The Air Force has funded an intensive effort (Contract AF 33(615)-3883) at Union Carbide Corporation to develop a sheet manufacturing process for this alloy. The material for this evaluation was supplied GFM from this effort. History and processing for the Udimet 700 sheet is contained in Reference 1. The specimens were heat-treated as follows:

- 2150F for 2 hours with rapid air cool,
- 1950F for 4 hours with ir cool,
- 1550 F for 24 hours with air cool,
- 1400 F for 16 hours with air cool.

According to Reference 1, this heat treatment is designed to give the best stress-rupture properties while maintaining good mechanical properties.

(1) Kelley, E. W., "Manufacturing Process for Improved High-Strength Superalloy Sheet", AFML-TR-69-114 (June 1969).

Udimet 700 Data[a]

Condition: STA
Thickness: 0.032-inch sheet

Properties	Temperature, F			
	RT	1000	1400	180
Tension				
TUS (longitudinal), ksi	224.7	213.0	127.3	26.
TUS (transverse), ksi	213.7	199.7	127.7	26.
TYS (longitudinal), ksi	150.7	139.7	121.3	22.
TYS (transverse), ksi	150.0	138.3	124.7	22.
e_t (longitudinal), percent in 2 in.	21.7	15.7	34.7	44.
e_t (transverse), percent in 2 in.	21.0	16.7	26.7	40.
E_t (longitudinal), 10^6 psi	32.9	29.1	23.2	13.
E_t (transverse), 10^6 psi	34.1	31.7	25.4	13.
Compression				
CYS (longitudinal), ksi	161.3	146.7	125.0	21.
CYS (transverse), ksi	161.0	147.7	125.0	21.
E_c (longitudinal), 10^6 ksi	33.5	31.0	24.3	12.
E_c (transverse), 10^6 ksi	36.2	33.0	24.6	11.
Shear[b]				
SUS (longitudinal), ksi	143.2	U[c]	U	U
SUS (transverse), ksi	148.0	U	U	U
Bend				
Longitudinal, minimum radius	1.5-2t	U	U	U
Transverse, minimum radius	1.5-2t	U	U	U
Fracture Toughness, K_c[d]	2.0	U	U	U
ksi$\sqrt{in.}$				
Axial Fatigue (transverse)				
Unnotched, R = 0.1[e]				
10^3 cycles, ksi	200	190	162	U
10^6 cycles, ksi	152	140	136	U
10^7 cycles, ksi	80	126	96	U
Notched, K_t = 3.0, R = 0.1				
10^3 cycles, ksi	158	140	110	U
10^6 cycles, ksi	75	68	68	U
10^7 cycles, ksi	42	52	60	U
Creep (transverse)				
0.2% plastic deformation, 100 hr	NA[c]	150	35	0.
0.2% plastic deformation, 1000 hr	NA	100	12	0.

Udimet 700 Data (Continued)

Properties	Temperature, F			
	RT	1000	1400	1800
Stress Rupture (transverse)				
Rupture, 100 hr	NA	180	60	3.5
Rupture, 1000 hr	NA	150	38	1.5
Stress Corrosion				
80% TYS, 1000-hour maximum	No cracks(f)			
Coefficient of Thermal Expansion				
8.0×10^{-6} in./in./F (RT to 1200 F)				
Density				
0.285 lb/in.^{3}				

(a) Each value given is the average of at least three tests conducted at Battelle under the subject contract, unless otherwise indicated. Fatigue, creep, and stress-rupture values are from curves generated using a greater number of tests.

(b) Single-shear sheet-type test.

(c) U, unavailable, NA, not applicable.

(d) Specimens were full sheet thickness x 18 in. x 48 in. with EDM flaw in center. The net section yield stress at fracture was less than the tensile yield strength of the material; therefore, the K values are considered valid.

(e) "R" represents the algebraic ratio of minimum stress to maximum stress in one cycle; i.e., $R = S_{min}/S_{max}$. "K_t" represents the Neuber-Peterson theoretical stress concentration factor.

(f) Room-temperature three-point bend test. Alternate immersion in 3½ percent NaCl.

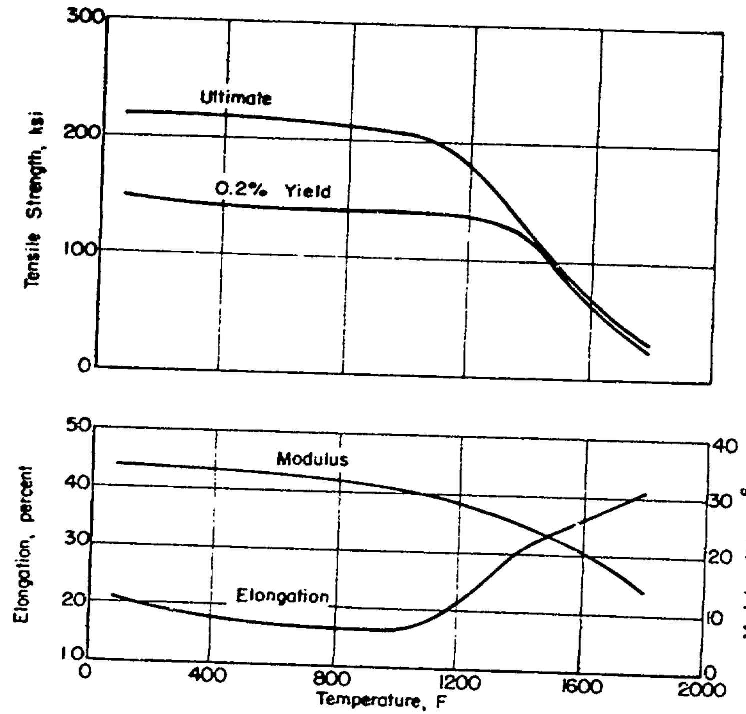

FIGURE 1. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF U-700 SHEET

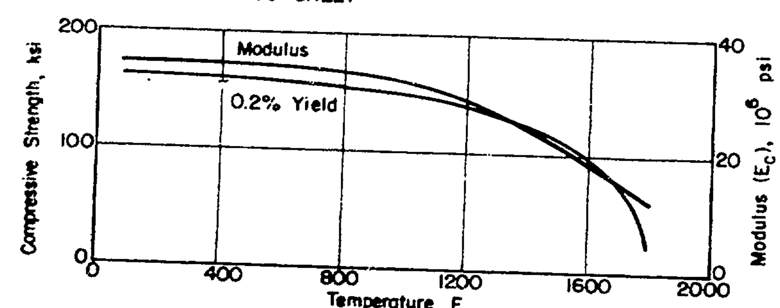

FIGURE 2. EFFECT OF TEMPERATURE ON THE COMPRESSION PROPERTIES OF U-700 SHEET

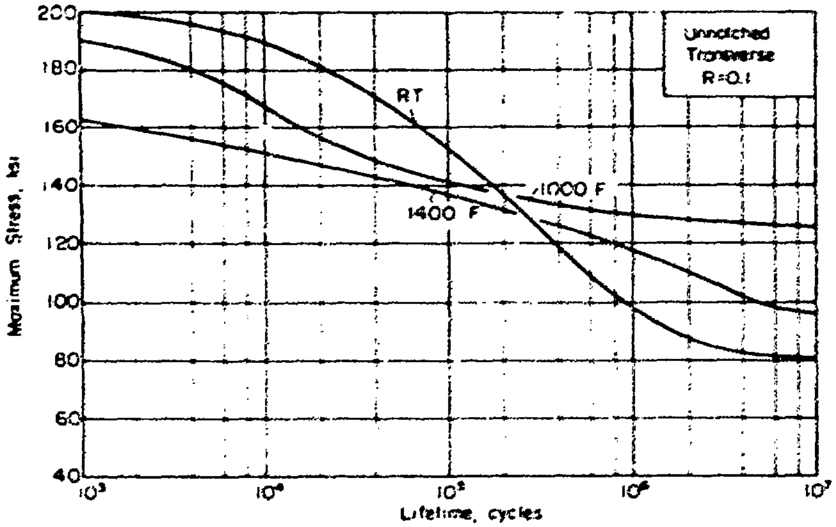

FIGURE 3 AXIAL-LOAD FATIGUE RESULTS FOR U-700 SHEET

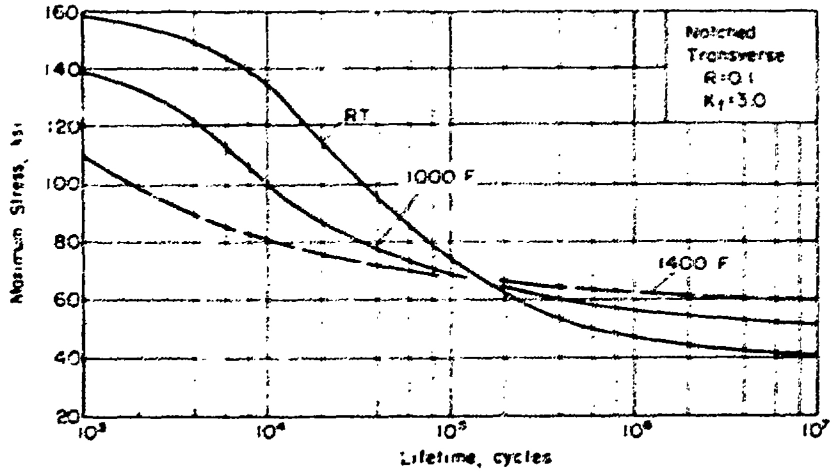

FIGURE 4 AXIAL-LOAD FATIGUE RESULTS FOR NOTCHED (K_t=3.0) U-700 SHEET

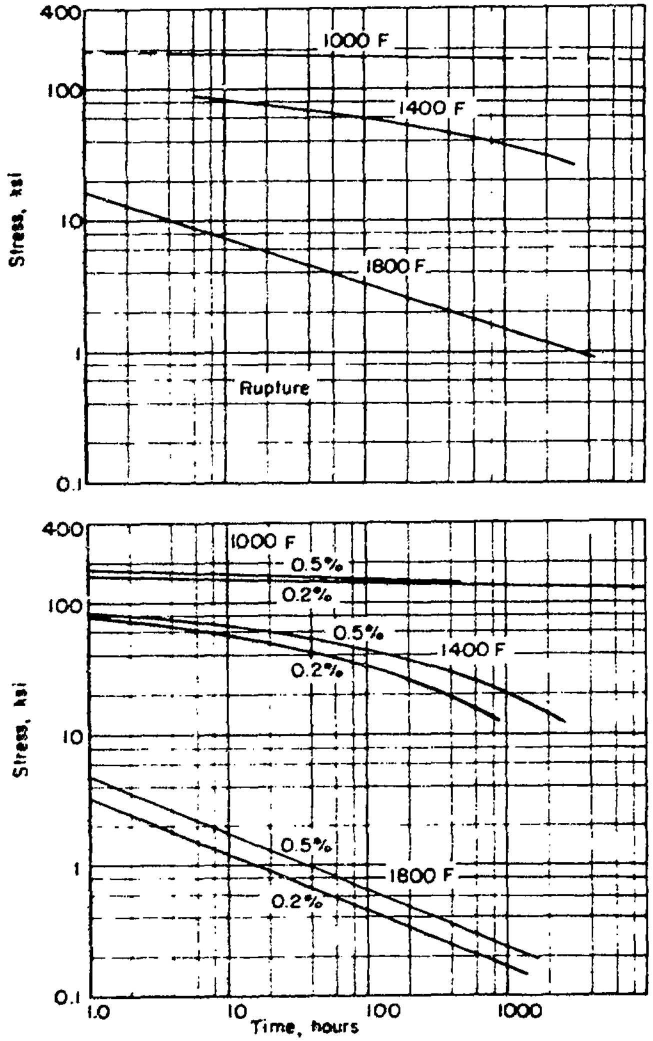

FIGURE 5. STRESS-RUPTURE AND PLASTIC DEFORMATION CURVES FOR UDIMET-700 AT THREE TEMPERATURES

Ti - 6 Al - 2 Sn - 4 Zr - 2 Mo Alloy

This is one of the so-called "super" alpha alloys having an alpha-stabilized Ti-Al matrix solid solution strengthened by the additions of tin and zirconium. The beta-stabilizing addition, molybdenum, increases room and elevated temperature tensile strength and stability. It was developed originally for jet engine usage, principally as forgings, however, it has also been produced as flat-rolled products. The alloy possesses good strength and stability up to 1000 F. Its formability and weldability compare favorably with other titanium alloys.

The composition of the material used in this evaluation was as follows.

C	Fe	N	Al	Mo	H	Zr	Sn	O
0.024	0.05	0.008	5.9	2.0	0.007	4.2	2.1	0.10

Ti
Balance

Ti - 6 Al - 2 Sn - 4 Zr - 2 Mo Data[a]

Condition: Triplex-annealed
Thickness: 0.080-inch sheet

Properties	RT	400	700	1000
	Temperature, F			
Tension				
TUS (longitudinal), ksi	146.3	129.0	120.0	102.6
TUS (transverse), ksi	147.6	129.0	120.0	103.3
TYS (longitudinal), ksi	144.3	109.6	94.1	83.4
TYS (transverse), ksi	145.6	111.6	97.0	86.0
e_t (longitudinal), percent in 2 in.	3.0	10.8	11.5	17.2
e_t (transverse), percent in 2 in.	2.7	10.7	10.8	16.5
E_t (longitudinal), 10^6 psi	17.0	15.9	14.3	12.2
E_t (transverse), 10^6 psi	17.9	16.7	14.9	13.5
Compression				
CYS (longitudinal), ksi	156.3	116.0	101.0	91.7
CYS (transverse), ksi	168.6	125.0	108.6	101.0
E_c (longitudinal), 10^6 psi	18.6	17.5	15.4	14.1
E_c (transverse), 10^6 psi	19.9	18.3	16.5	15.2
Shear[b]				
SUS (longitudinal), ksi	100.0	U[c]	U	U
SUS (transverse), ksi	101.0	U	U	U
Fracture Toughness, K_c				
ksi $\sqrt{\text{in.}}$	135[d]	U	U	U
Axial Fatigue (transverse)[e]				
Unnotched, R = 0.1				
10^3 cycles, ksi	102	102	101	U
10^5 cycles, ksi	40	50	40	U
10^7 cycles, ksi	25	32	32	U
Notched, K_t = 3.0, R = 0.1				
10^3 cycles, ksi	69	75	75	U
10^5 cycles, ksi	22	26	22	U
10^7 cycles, ksi	10	10	10	U
Creep (transverse)				
0.2% plastic deformation, 100 hr	NA[c]	106.0	99.0	20.0
0.2% plastic deformation, 1000 hr	NA	105.0	93.0	9.2

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Ti - 6 Al - 2 Sn - 4 Zr - 2 Mo Data (continued)

Properties	RT	400	700	1000
		Temperature, F		
Stress Rupture (transverse)				
Rupture, 100 hr	NA	129.0	118.0	62.0
Rupture, 1000 hr	NA	121.0	117.0	37.0
Stress Corrosion				
60% TYS, 1000-hr maximum	No cracks(f)			
Coefficient of Thermal Expansion				
5.4×10^{-6} in/in/F (RT to 1000 F)				
Density				
0.164 lb/in.^{3}				

(a) Values are average of triplicate tests conducted at Battelle under the subject contract unless otherwise indicated. Fatigue, creep, and stress-rupture values are from curves generated using the results of a greater number of tests.

(b) Single shear sheet type specimens.

(c) U, unavailable, NA, not applicable.

(d) Specimens were full sheet thickness x 1+ inches x 3+ inches with EDM slot in center. The net section yield stress at fracture was less than the tensile yield strength of the material. The K value is considered valid.

(e) "R" represents the algebraic ratio of minimum stress to maximum stress in one cycle, that is, $R = S_{min}/S_{max}$. "K_t" represents the Neuber-Peterson theoretical stress concentration factor.

(f) Room-temperature three-point bent test. Alternate immersion in 3-1/2% NaCl.

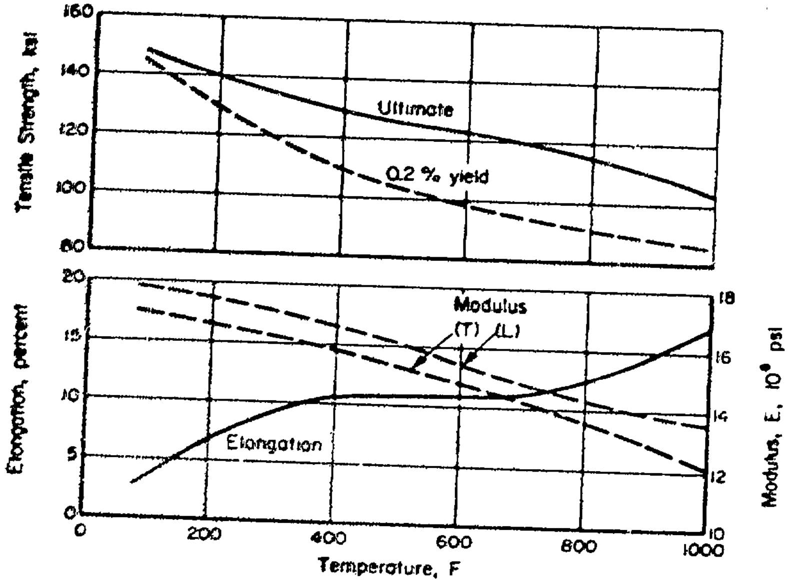

FIGURE 1 EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF Ti-6Al-2Sn-4Zr-2Mo SHEET

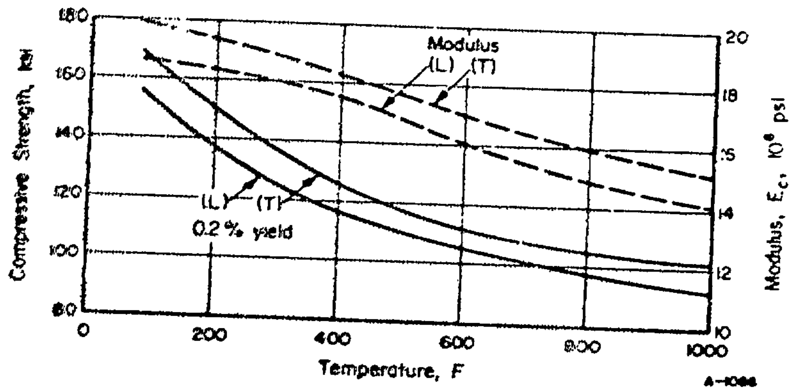

FIGURE 2. EFFECT OF TEMPERATURE ON THE COMPRESSIVE PROPERTIES OF Ti-6Al-2Sn-4Zr-2Mo SHEET

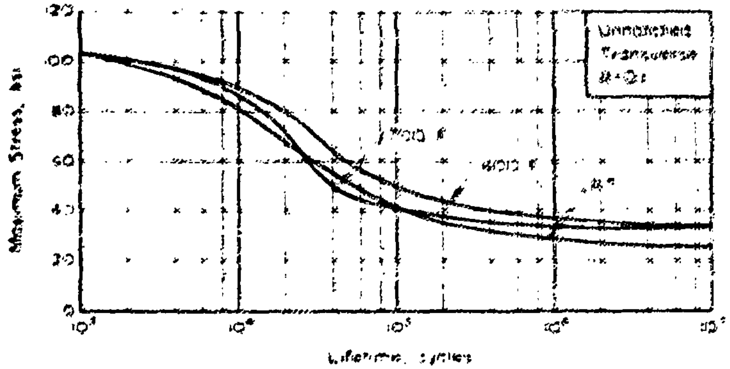

FIGURE 3. AXIAL LOAD FATIGUE RESULTS FOR Ti-6Al-2Sn-4Zr-2Mo SHEET

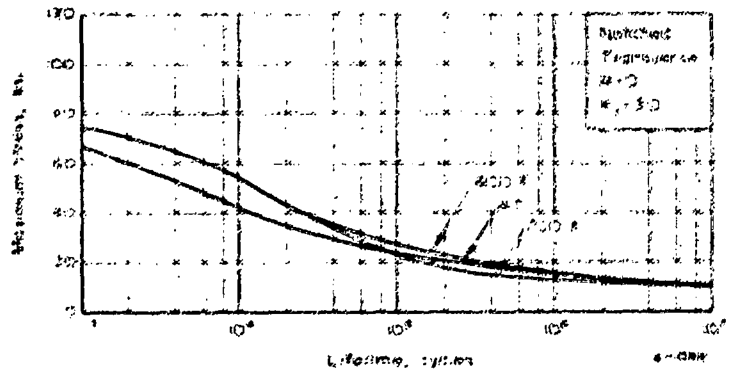

FIGURE 4. AXIAL LOAD FATIGUE RESULTS FOR NOTCHED (K_t = 3.0) Ti-6Al-2Sn-4Zr-2Mo SHEET

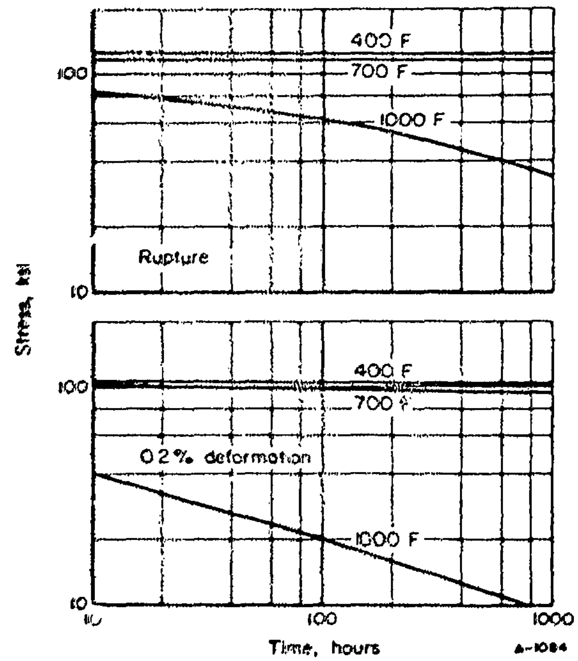

FIGURE 5. STRESS-RUPTURE AND PLASTIC DEFORMATION CURVES FOR Ti-6Al-2Sn-4Zr-2Mo SHEET

PH 14-8 Mo Alloy

PH 14-8 Mo is a recent addition to the Armco Steel Company's family of precipitation hardenable stainless steels. It is a semiaustenitic alloy developed to provide a sheet and strip product with higher resistance to crack propagation than the older 17-7PH and PH15-7 Mo alloys. It is heat treatable to high strengths and exhibits good elevated temperature properties. Since it is austenitic in the annealed condition, it is readily formable by methods currently used for austenitic or other semiaustenitic steels. The alloy does work harden rapidly and may require intermediate anneals for deep drawn or other severly formed parts.

The alloy is commercially available in the form of sheet and strip.

The composition of the material used for this evaluation was as follows.

C	Mn	P	S	Si	Cr	Ni	Mo	Al	Fe
0.038	0.10	0.003	0.004	0.10	14.95	8.31	2.15	1.17	Balance

PH 14-8 Mo Data(a)

Condition: SRH 1050
Thickness: 0.070-inch sheet

Properties	RT	Temperature, F 400	700	900
Tension				
TUS (longitudinal), ksi	203.3	182.3	164.3	131.0
TUS (transverse), ksi	207.3	185.6	167.6	134.0
TYS (longitudinal), ksi	199.3	173.6	152.0	119.0
TYS (transverse), ksi	201.8	177.0	156.3	123.7
e_t (longitudinal), percent in 2 in.	7.5	6.0	9.6	18.2
e_t (transverse), percent in 2 in.	7.2	5.4	8.1	15.6
E_t (longitudinal), 10^6 psi	27.2	26.0	25.5	23.1
E_t (transverse), 10^6 psi	28.6	28.4	26.1	23.5
Compression				
CYS (longitudinal), ksi	218.3	197.6	176.5	137.6
CYS (transverse), ksi	219.0	203.0	180.6	146.6
E_c (longitudinal), 10^6 psi	27.6	25.5	25.2	24.4
E_c (transverse), 10^6 psi	30.5	27.1	26.3	25.7
Shear(b)				
SUS (longitudinal), ksi	130.2	U(c)	U	U
SUS (transverse), ksi	129.0	U	U	U
Bend				
minimum radius	IT	U	U	U
Fracture Toughness, K_c				
ksi $\sqrt{\text{in.}}$	270(d)	U	U	U
Axial Fatigue (transverse)(e)				
Unnotched, R = 0.1				
10^3 cycles, ksi	190	185	170	U
10^5 cycles, ksi	102	92	86	U
10^7 cycles, ksi	90	80	76	U
Notched, K_t = 3.0, R = 0.1				
10^3 cycles, ksi	119	117	110	U
10^5 cycles, ksi	41	38	44	U
10^7 cycles, ksi	30	30	40	U

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PH 14-8 Mo Data (continued)

Properties	Temperature, F RT	400	700	900
Creep (transverse)				
0.2% plastic deformation, 100 hr	NA(c)			
0.2% plastic deformation, 1000 hr	NA			
Stress Rupture (transverse)				
Rupture, 100 hr	NA			
Rupture, 1000 hr	NA			
Stress Corrosion(f)				
80% TYS, 1000-hr maximum	*No cracks*			
Coefficient of Thermal Expansion				
10^{-6} in/in/F = (70-200 F) 5.3				
(70-600 F) 6.2				
(70-1000 F) 6.4				
Density				
0.278 lb/in.^{3}				

(a) Values are average of triplicate tests conducted at Battelle under the subject contract unless otherwise indicated. Fatigue, creep, and stress rupture values are from curves generated using a greater number of tests.

(b) Single shear sheet type specimen.

(c) U, unavailable; NA, not applicable.

(d) Specimens were full sheet thickness x 18 inches x 36 inches with EDM flow in center. The net section yield stress at fracture was less than the tensile yield strength of the material. The K value is considered valid.

(e) "R" represents the algebraic ratio of minimum stress to maximum stress in one cycle; that is, $R = S_{min}/S_{max}$. "K_t" represents the Neuber-Peterson theoretical stress concentration factor.

(f) Room-temperature three-point bend test. Alternate immersion in 3-1/2% NaCl.

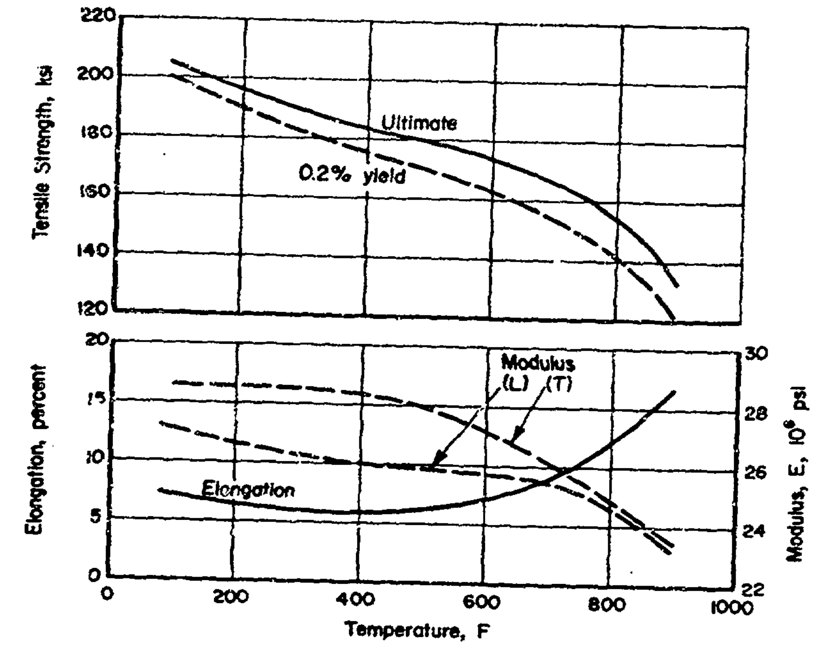

FIGURE 1. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF PH 14-8 Mo SHEET

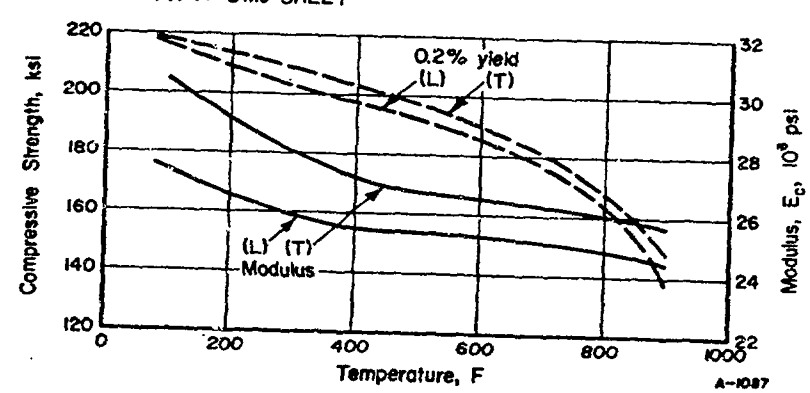

FIGURE 2. EFFECT OF TEMPERATURE ON THE COMPRESSIVE PROPERTIES OF PH 14-8 Mo SHEET

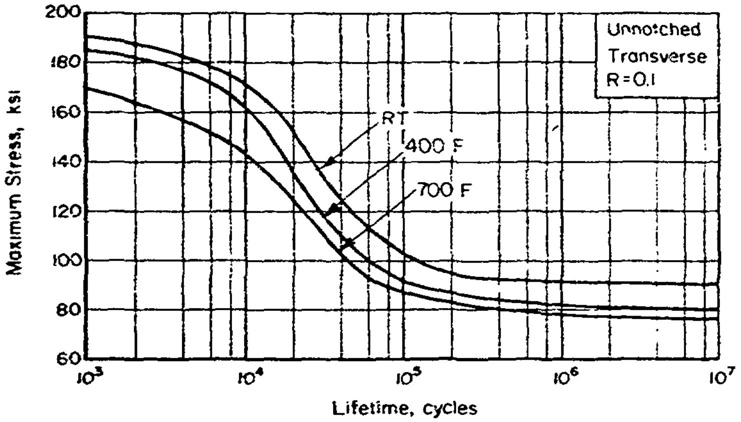

FIGURE 3. AXIAL LOAD FATIGUE RESULTS FOR PH 14-8Mo SHEET

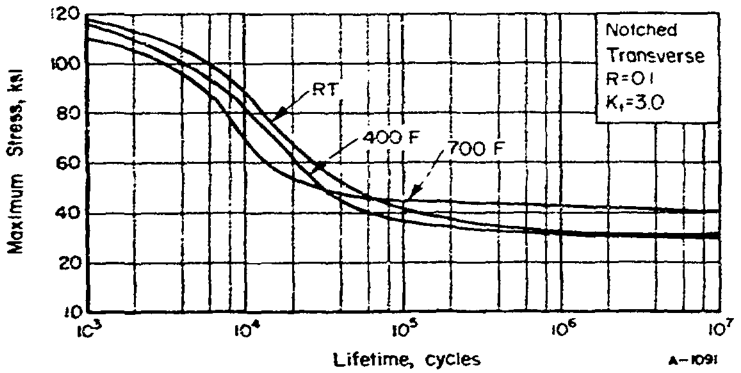

FIGURE 4. AXIAL LOAD FATIGUE RESULTS FOR NOTCHED (K_t=3.0) PH 14-8 Mo SHEET

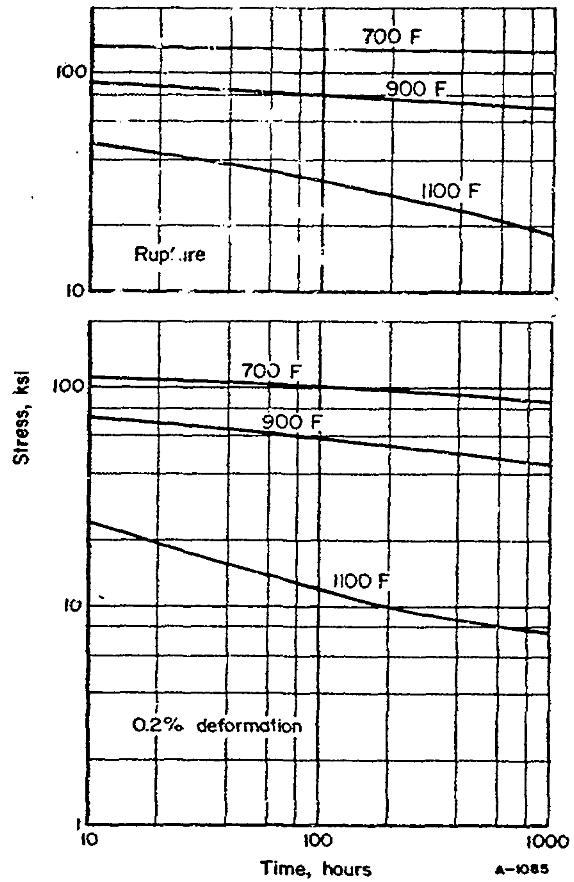

FIGURE 5. STRESS-RUPTURE AND PLASTIC DEFORMATION CURVES FOR PH 14-8Mo SHEET